AD690931

28

EDR 6301

# PHASE I
# LIGHTWEIGHT GEARBOX
# COMPOSITE CASE

## Final Report
## (29 June 1968 to 29 June 1969)

30 June 1969

By

G. H. Kempinger
D. A. Wagner

Distribution of this document is unlimited

Prepared Under Contract N00019-68-C-0514

for

Naval Air Systems Command
Department of the Navy



by

**Allison Division • General Motors**

**Indianapolis, Indiana**



61

EDR 6301

# PHASE I
# LIGHTWEIGHT GEARBOX
# COMPOSITE CASE

## Final Report
## (29 June 1968 to 29 June 1969)

30 June 1969

By

G. H. Kempinger
D. A. Wagner

Distribution of this document is unlimited

Prepared Under Contract N00019-68-C-0514

for

Naval Air Systems Command
Department of the Navy

by

Allison Division • General Motors

Indianapolis, Indiana

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF TABLES

# I. INTRODUCTION

This report is submitted as the Phase I summary report in compliance with Contract N00019-68-C-0514. The work accomplished by Allison Division and Goodyear Aerospace Corporation on designing and molding an advanced lightweight boron-glass-epoxy composite reduction gear front gear case is described herein. The program period covered by this report is from 22 July 1968 through 30 June 1969.

Design and development of a molded, composite material gear case was proposed to the Naval Air Systems Command during January 1968. The proposal presented a two-phase program to design, mold, machine and test a front gear case adaptable to the T56-A-18 reduction gear assembly. Phase I consisted of designing and compression molding three composite material front gear cases. Phase II proposed machining and assembling the best of three molded cases and comparative deflection and endurance testing with the magnesium case. Effort reported herein covers Phase I Design by Allison Division and mold fabrication by Goodyear Aerospace Corporation.

## II. SUMMARY AND RECOMMENDATIONS

The feasibility of molding boron-glass-epoxy composite material gear cases has been successfully demonstrated under Contract N00019-68-C-0514. Two cases designed to be adaptable to the T56-A-18 reduction gear assembly were developed under Contract AF33(657)-11532 and finish molded with excellent results. Local epoxy-rich areas and small voids in the flange area as a result of filament flow interference warranted the discontinuance of the final molding operation on one of the three cases.

The design of the composite gear case used the high modulus advantage of boron for structural stiffness. Analytical techniques were developed for case deflection and checked against T56-A-18 reduction gear development program test results. These techniques were employed to position continuous-collimated and random-oriented fiber to increase gear case bending stiffness. The resultant case design is 13% lighter and approximately twice as stiff as its magnesium counterpart.

All aspects of the program from design through molding either preceded or met scheduled milestones. Primary phases were design completion and reporting in November 1968, tooling completion in March 1969, and die tryout and first composite molding in May 1969.

Composite material technology, now in its infancy, requires progressive research and development to fully evaluate the potential for industrial use. Programs specifically requiring direction toward this goal are materials evaluation, processing evaluation, and inspection procedures.

Material properties must be defined by valid specifications and substantiated by testing to optimize future design undertakings. Bare fiber materials (other than boron) which are worthy of recommendation for specification documentation include graphite and beryllium. Graphite is most deserving of evaluation because of advantages in cost, availability, handling, processing, and molding; at the same time graphite retains the strength properties of boron.

Composite processing techniques as well as material properties lack defined specifications. It is recommended that, for quality assurance, such molding factors as material distribution, pressures, and curing temperature cycles be developed to provide process specifications for composite materials.

Another area in composites requiring definition is inspection. Allison has conducted the following preliminary nondestructive inspections:

- X-ray
- Dye penetrant
- Thermographic
- Ultrasonic
- Neutron radiography

The results of using these inspection procedures on composite materials can only be interpreted on the basis of experience. However, at the present, there is insufficient experience for consistent results.

Inspection procedures will have to be developed for composite materials so that product quality can be guaranteed.

# III. COMPOSITE CASE DESIGN

The need for new case materials to meet the high structural loads dictated by propeller and engine mounting requirements has long been recognized by Allison. Magnesium with reasonable strength and low density has the disadvantage of poor corrosion resistance. Aluminum with adequate strength is heavy for most applications. Review of technology in lightweight gear case materials showed that recently developed composite materials offered advantages in strength, stiffness, density and corrosion resistance. The composite material selected for evaluation on this program was boron and glass fiber with epoxy resin binder. Table 3-I compares the density and strength properties of this composite with magnesium.

Table 3-I.
Comparison of density and strength properties for magnesium and boron-glass-epoxy composite.

| | Magnesium | Boron-glass-epoxy composite: Unidirectional fiber | Boron-glass-epoxy composite: Random fiber |
|---|---|---|---|
| Density, $lb/in.^3$ | 0.066 | 0.077 | 0.077 |
| Ultimate strength, psi | 34,000 | 200,000 | 60,000 |
| Young's modulus, psi | $6.5 \times 10^6$ | $30.5 \times 10^6$ | $12.0 \times 10^6$ |

## DESIGN REQUIREMENTS

The composite gear case was designed to be compatible with existing T56-A-18 hardware. See Figure 3-1 for the T56-A-18 reduction gear assembly. To obtain compatibility with the existing hardware, such interface features as bolt circles, bearing bores, and oil distribution ports were fixed by the previous design. However, the case wall and stiffening members left considerable latitude for adjustment and change in the design.

The front gear case provides the following main functions:

- Supports forward propeller bearing
- Supports main drive gear bearing
- Supports forward pinion bearing
- Transmits bearing loads to rear case and into gearbox mounts
- Retains main propeller shaft seal
- Provides integral oil passages for lube system

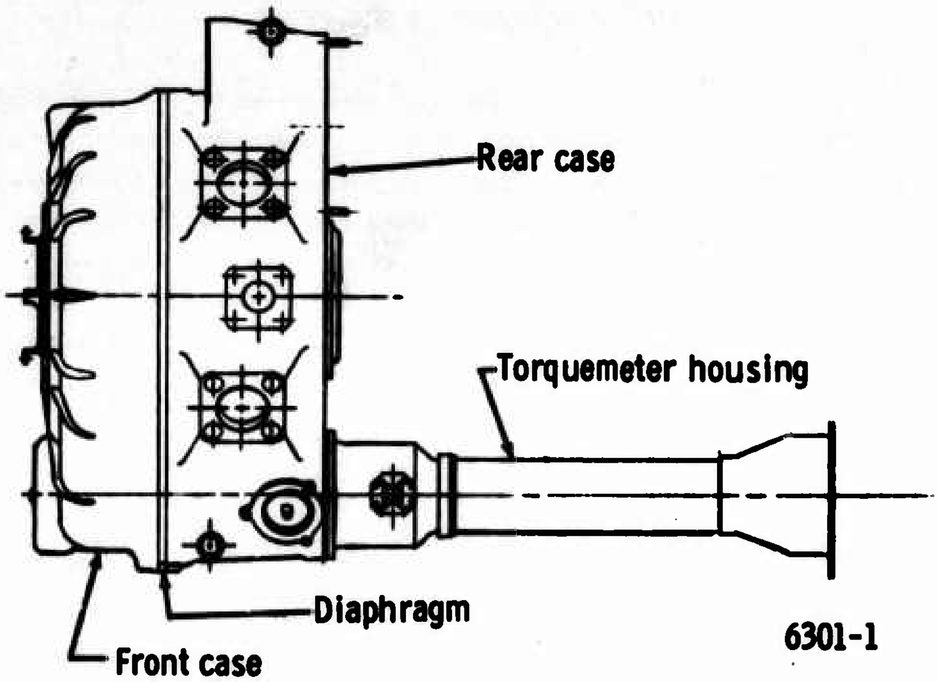



**Figure 3-1. T56-A-18 reduction gear assembly.**

Three bearings are supported in the front case. Two of the bearings are located in the plane of the front wall (front pinion and propeller bearing) and the radial loads from these two are carried as tensile loads in the front wall. The third bearing (main drive gear) is cantilevered from the front wall which results in bending moments in the front wall. Figure 3-2 shows the bearing loads reacted by the front case.

The propeller shaft imposes radial loads on the front case that could be in any radial direction. This load is a result of the 1XP propeller load which is caused by inflow to the propeller at an angle. The main drive gear and pinion impart loads to the case through the support bearings as a result of the tooth loads on the gears.

The pinion and main drive gear bearing loads are derived from the power transmitted and the geometry of the gears as shown in Table 3-II.

The total tooth load is also the load reacted by the pinion and main drive gear bearings. For the pinion this load is reacted on two bearings, one of which is in the front case; for the main drive gear the load is reacted by one bearing supported by the front case. This

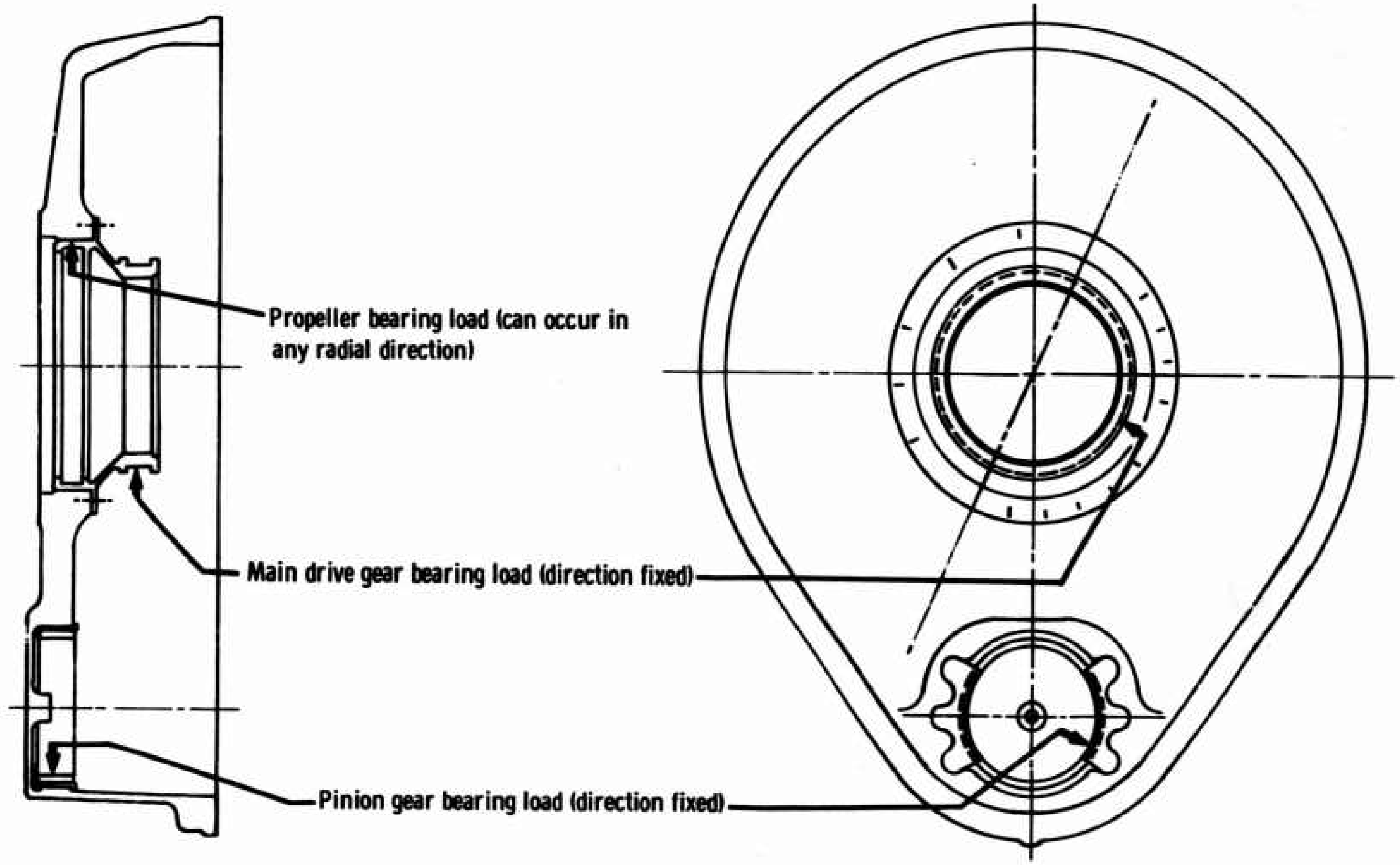



Figure 3-2. Bearing loads on front case.

Table 3-II.
Pinion and main drive gear geometry.

| | Pinion gear | Main drive gear |
|---|---|---|
| Pitch diameter, in. | 4.613 | 18.946 |
| Tooth pressure angle, degrees | 25.5 | 25.5 |

Input speed to the pinion is 13,820 rpm and the power transmitted is 5,500 horsepower. The pinion torque is, therefore:

$$\frac{5,500 \text{ hp} \times 63,025}{13,820 \text{ rpm}} = 25,100 \text{ in.-lb}$$

The pinion gear tooth tangential load ($W_t$) is obtained from the transmitted torque and gear pitch radius:

$$W_t = \frac{\text{Torque}}{\text{Pitch radius}} = \frac{25,100 \text{ in.-lb}}{2.3065} = 10,900 \text{ lb}$$

The total tooth load (W) is a function of the tooth pressure angle and tangential load:

$$W = \frac{W_t}{\cos \text{(pressure angle)}} = \frac{10,900 \text{ lb}}{\cos 25.5} = 12,050 \text{ lb}$$

---

one bearing is cantilevered from the front case which leads to bending moments in the front wall of the case. The maximum propeller 1XP moment was determined to be 225,000 in.-lb. This moment is reacted by two bearings with a spread of 12.9 in. The resulting propeller bearing load on the front case is:

$$\frac{225,000 \text{ in.-lb}}{12.9 \text{ in.}} = 17,500 \text{ lb}$$

The composite front case was designed to withstand without failure the previously described loads as well as keep deflections to a minimum. Excessive deflections of the front case will lead to misalignment of the gear train and bearings which, in turn, decreases the life and reliability of these components.

The load deflection characteristics of the magnesium front case were evaluated during the T56-A-18 development program by static test. The stiffness of the composite case was increased over that of the magnesium case. The analytical approach used to make this comparison is described later in the subsection, Stress and Deflection Analysis.

## CASE CONFIGURATION

The magnesium T56-A-18 front gear case has axial and circumferential ribs on both the inside and outside. During development testing of the gearbox, parasitic power losses were evaluated. A portion of these losses was attributed to churning of oil around and off the internal ribs on the front gear case.

A composite front case was designed without internal ribs to:

- Reduce power loss caused by oil churning
- Simplify the design of the male portion of the mold since it would not be necessary to machine rib grooves on that part of the mold

Two different designs were considered for the composite case.

- Syntactic foam* and composite
- All-composite

Figure 3-3 depicts the two types of composite construction along with the current magnesium construction.

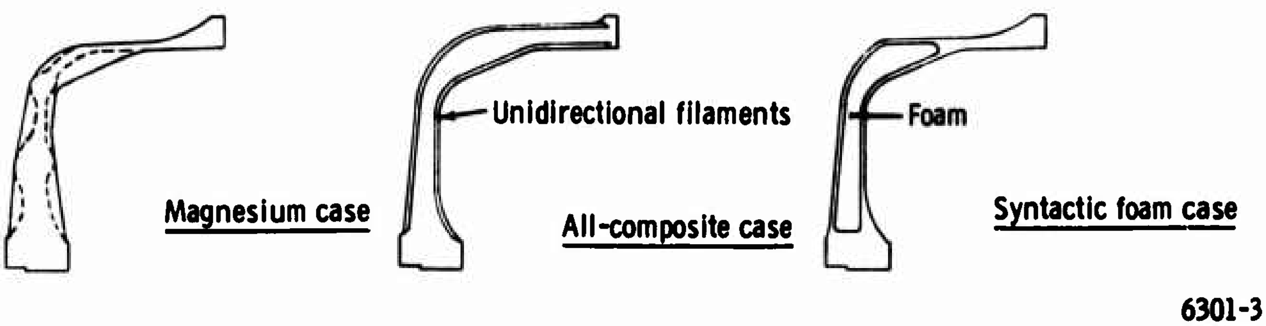



Figure 3-3. Three types of case construction.

*Syntactic foam is composed of hollow glass spheres with epoxy binder. Density of this material (depending on size of sphere) is 0.01 to 0.026 $lb/in.^3$.

Two potential advantages of using syntactic foam filler blocks were:

- Light weight
- Smooth external and internal walls

The foam filler blocks could lead to a very light case because they would allow positioning of the composite material in the most efficient locations.

The following disadvantages were sufficient to eliminate considerations of the use of syntactic foam.

- Two or three sets of molds are required.
- There is a low shear stress area at the parting line of foam and composite.
- Differential thermal growth exists between foam and composite.

The construction selected for the T56-A-18 front composite case is an all-composite material with ribs on the outside. The advantages of this type design are:

- One set of molds
- No low shear stress areas
- Simplified analytical analysis

The final configuration of the composite gear case is shown in layout form as Figure 3-4 and in detail form as Figure 3-5.

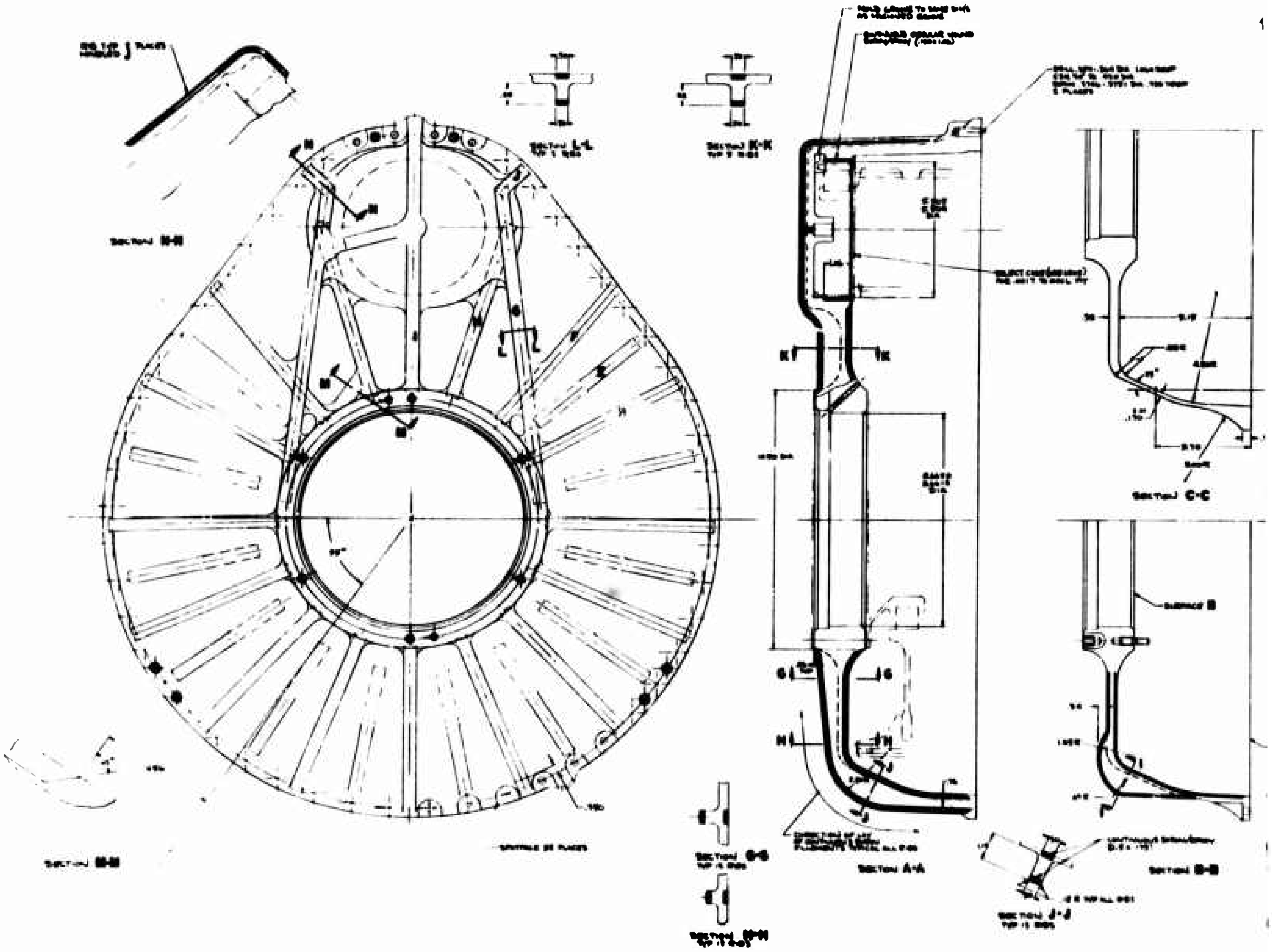
## DESIGN CONSIDERATIONS

### Material Properties and Composition

Two different compositions of boron-glass-epoxy composite were employed in the design of the composite gear case. Material properties for each composition, isotropic and anisotropic, are shown in Table 3-III.

The isotropic material consists of one-inch lengths of glass and boron fiber with epoxy resin binder. Orientation of the fibers is random, which leads to the isotropic material properties.

The anisotropic material consists of collimated, continuous filaments of boron fiber layed up in plys on glass cloth, one sheet of cloth per layer of boron filament. Glass and boron are impregnated with epoxy resin binder. See Figure 3-6.


SECTION L-L
SECTION K-K
SECTION C-C
SECTION A-A
SECTION B-B
SECTION G-G
SECTION J-J

A.

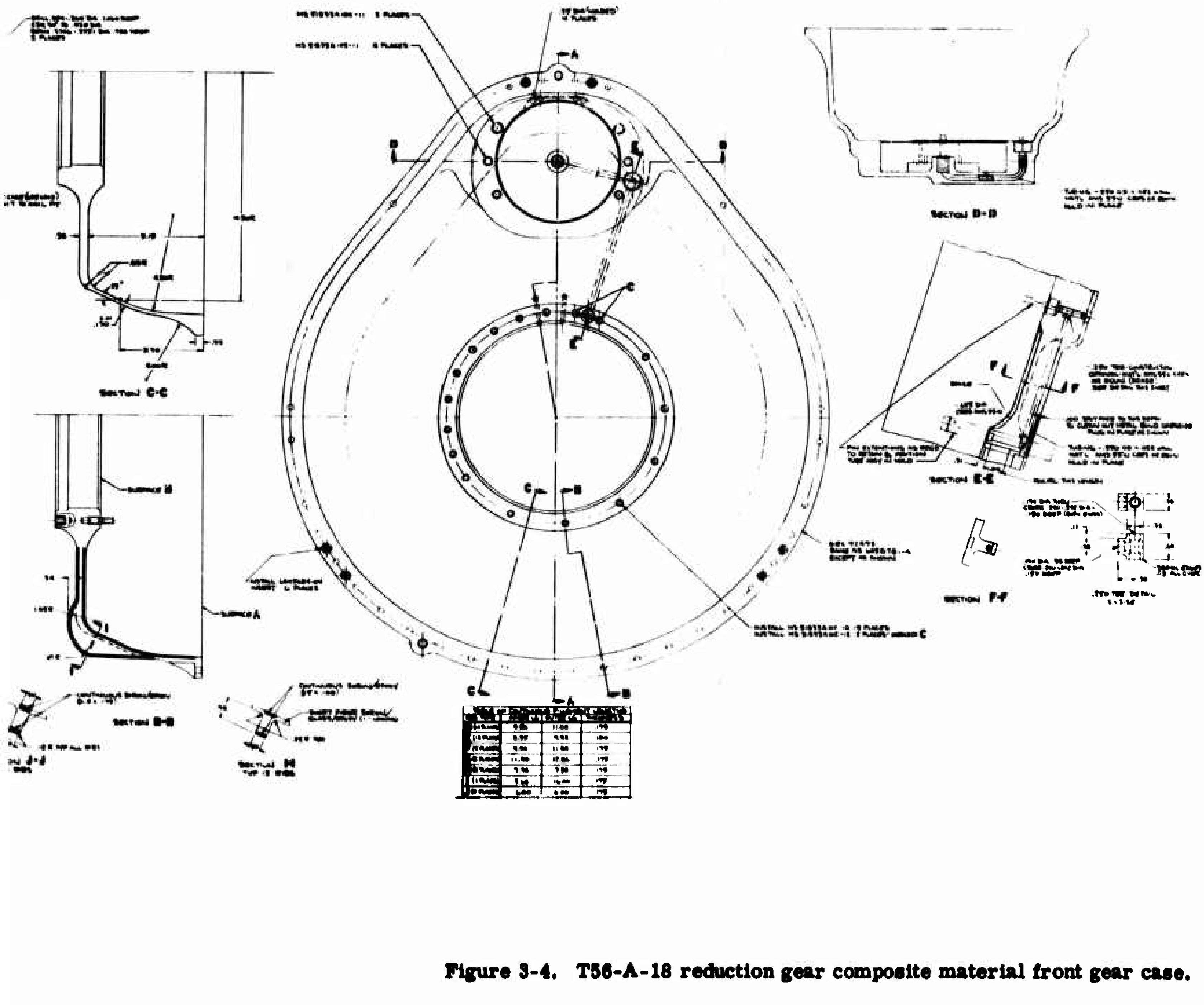


**Figure 3-4. T56-A-18 reduction gear composite material front gear case.**



B.

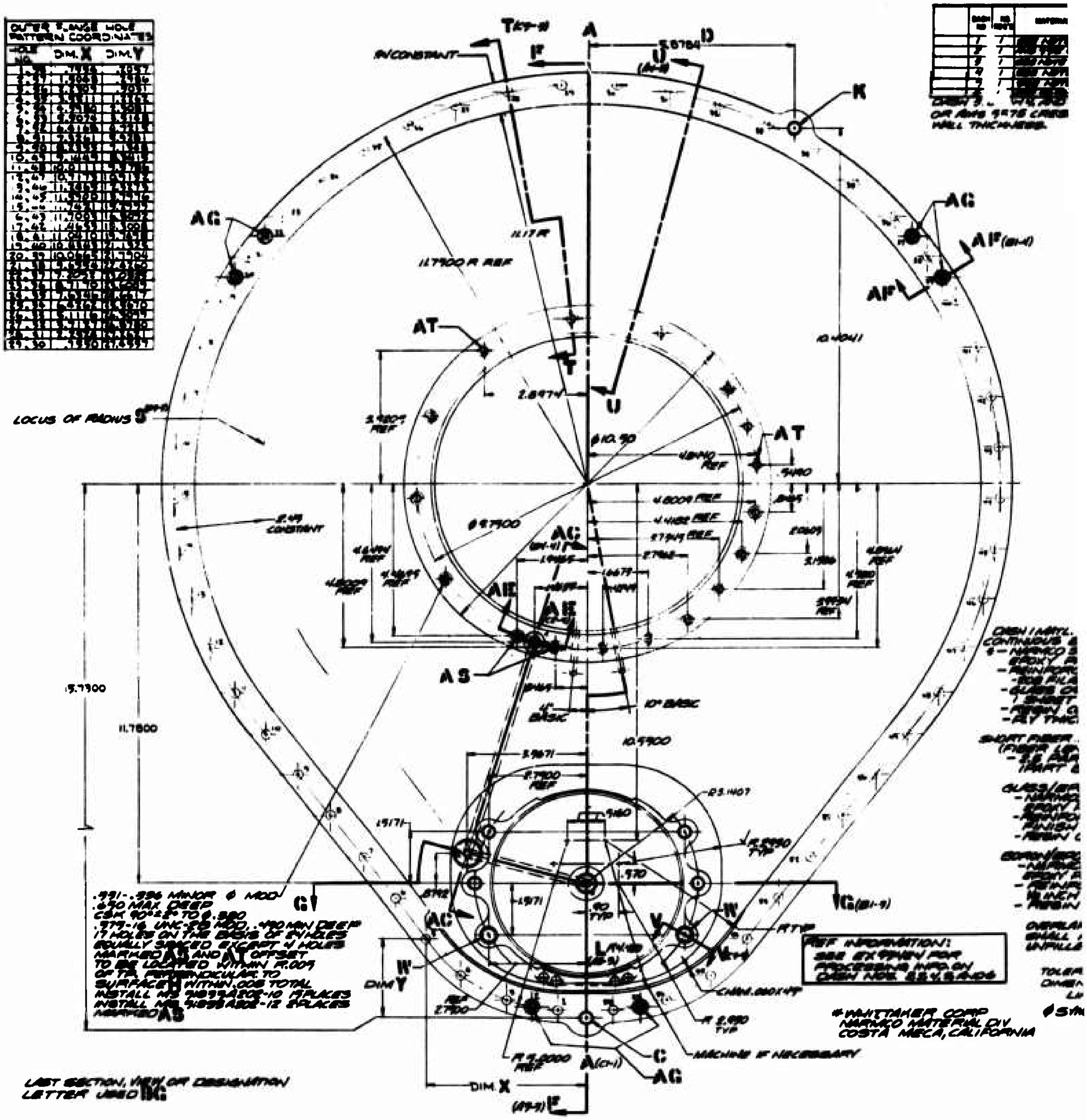



**Figure 3-5. T56-A-18 reduction gear**
**(Shee**

A.

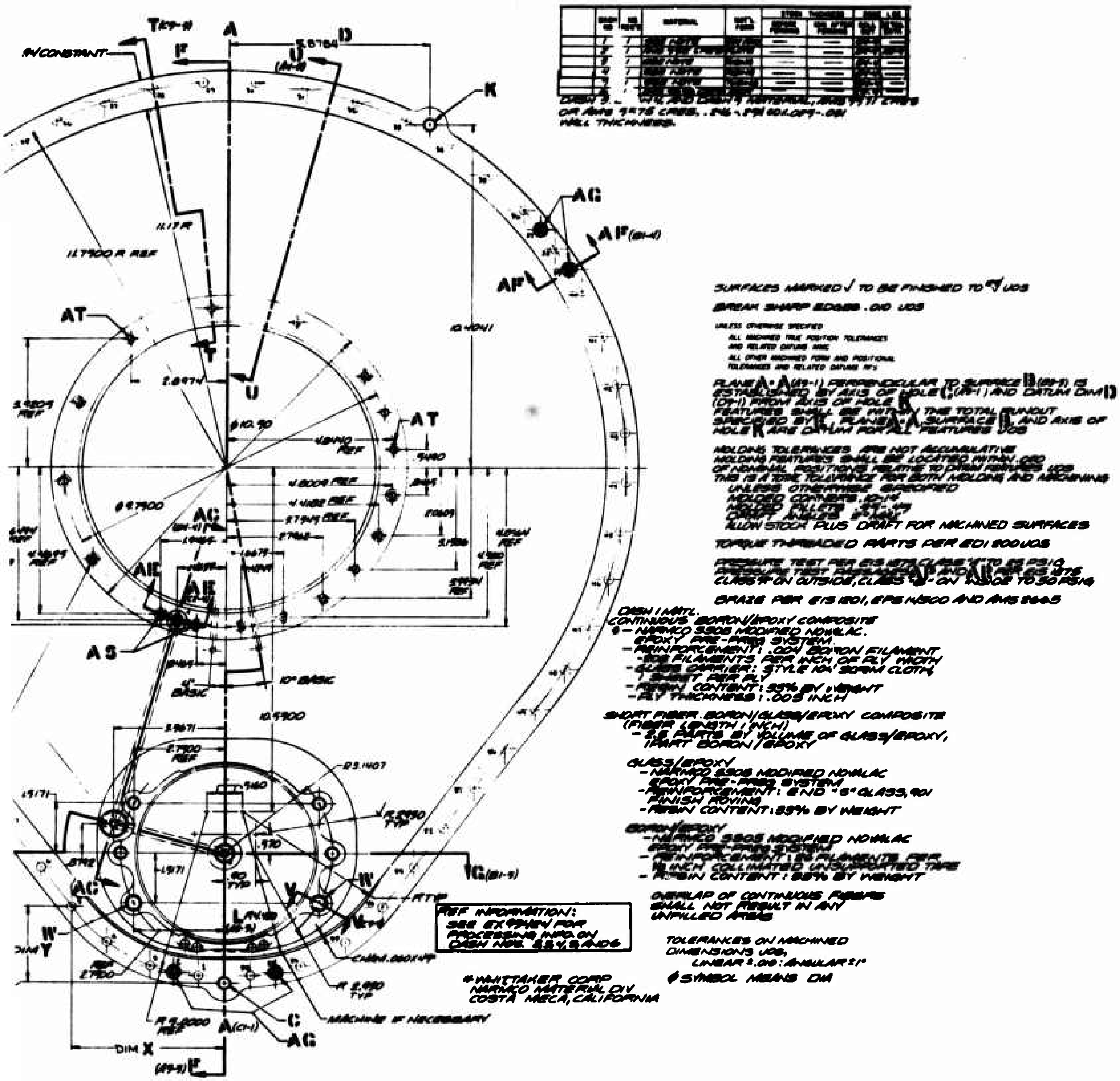
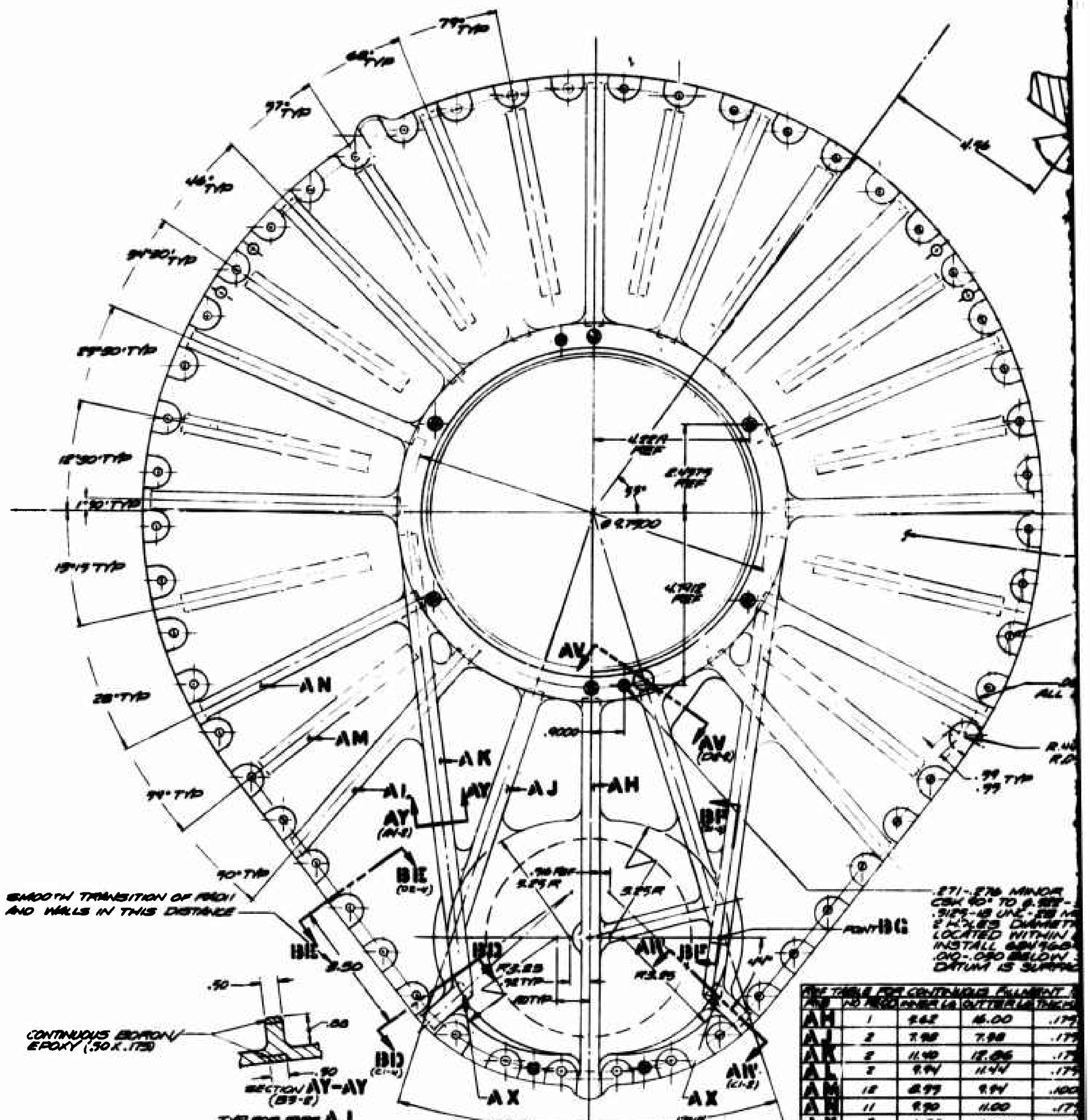


Figure 3-5. T56-A-18 reduction gear composite material front gear case details. (Sheet 1 of 4)



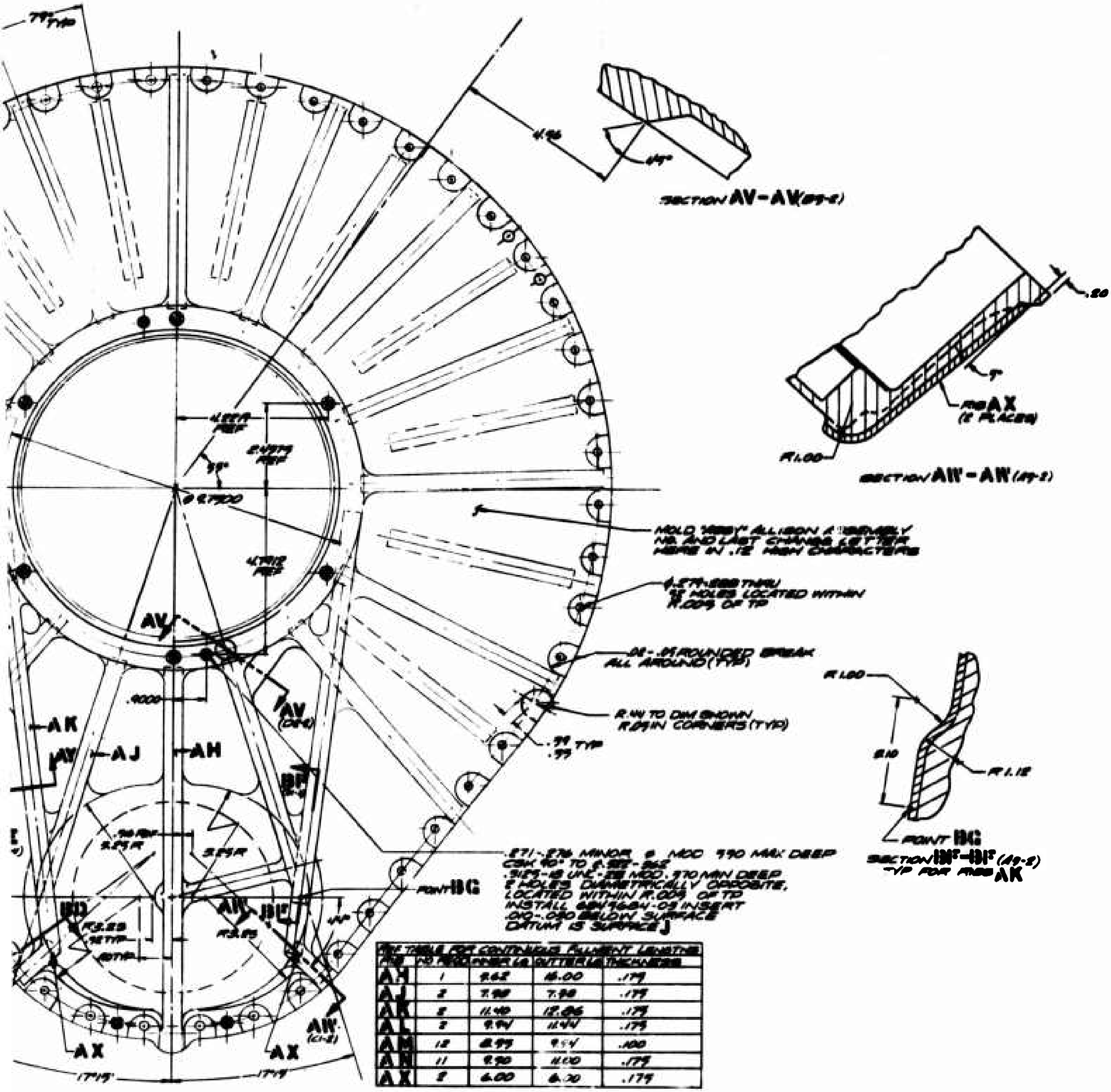
B.




| RIB TABLE FOR CONTINUOUS FILAMENT | | | | |
|---|---|---|---|---|
| RIB | NO. REQD | INNER LG | OUTTER LG | THICK |
| AH | 1 | 9.62 | 16.00 | .17 |
| AJ | 2 | 7.98 | 7.98 | .17 |
| AK | 2 | 11.40 | 12.86 | .17 |
| AL | 2 | 9.94 | 11.44 | .17 |
| AM | 12 | 8.99 | 9.94 | .100 |
| AN | 11 | 9.90 | 11.00 | .17 |
| AX | 2 | 6.00 | 6.00 | .17 |

**Figure 3-5. T56-A-18 reduction gear**
**(She**

A.




| TABLE FOR CONTINUOUS FILAMENT LENGTHS | | | | |
|---|---|---|---|---|
| RIB | NO PIECES | INNER LG | OUTTER LG | THICKNESS |
| AH | 1 | 9.62 | 16.00 | .179 |
| AJ | 2 | 7.98 | 7.98 | .179 |
| AK | 2 | 11.40 | 12.86 | .179 |
| AL | 2 | 9.94 | 11.44 | .179 |
| AM | 12 | 8.99 | 9.54 | .100 |
| AN | 11 | 9.90 | 11.00 | .179 |
| AX | 2 | 6.00 | 6.30 | .179 |

**Figure 3-5. T56-A-18 reduction gear composite material front gear case details. (Sheet 2 of 4)**



B.

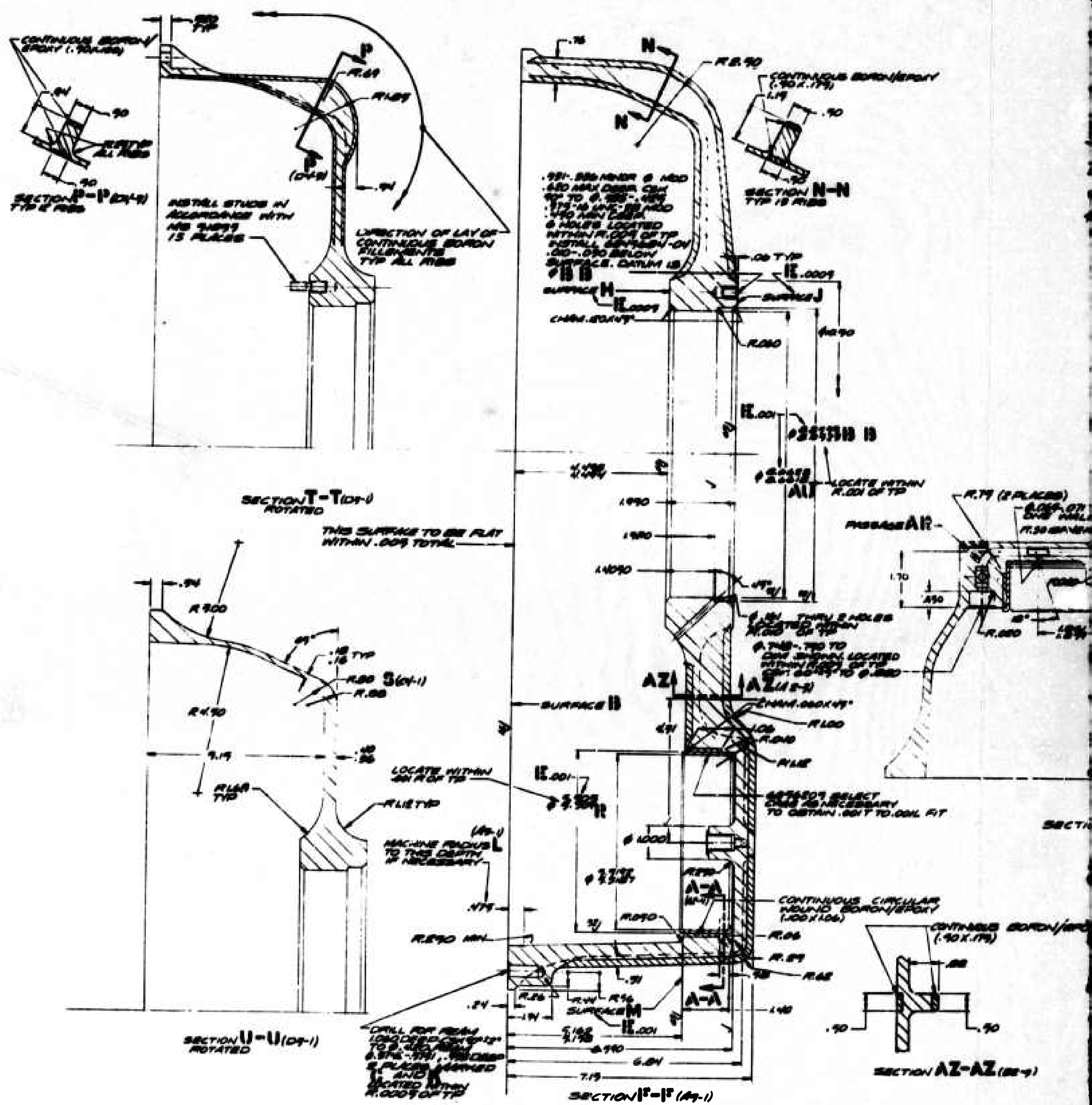
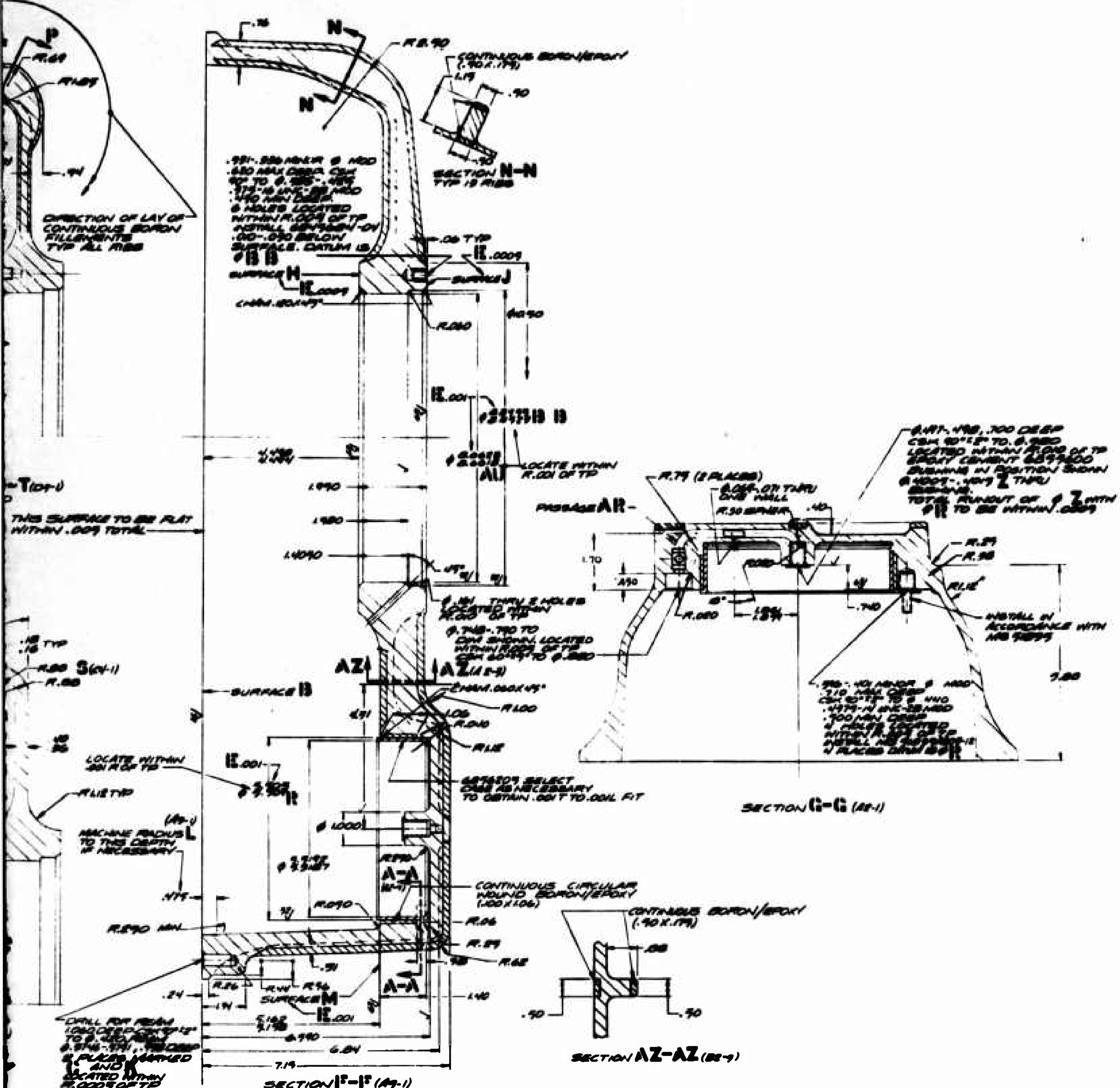


Figure 3-5. T56-A-18 reduction gear compo

(Sheet 3 of

A₁




B.

**Figure 3-5. T56-A-18 reduction gear composite material front gear case details. (Sheet 3 of 4)**

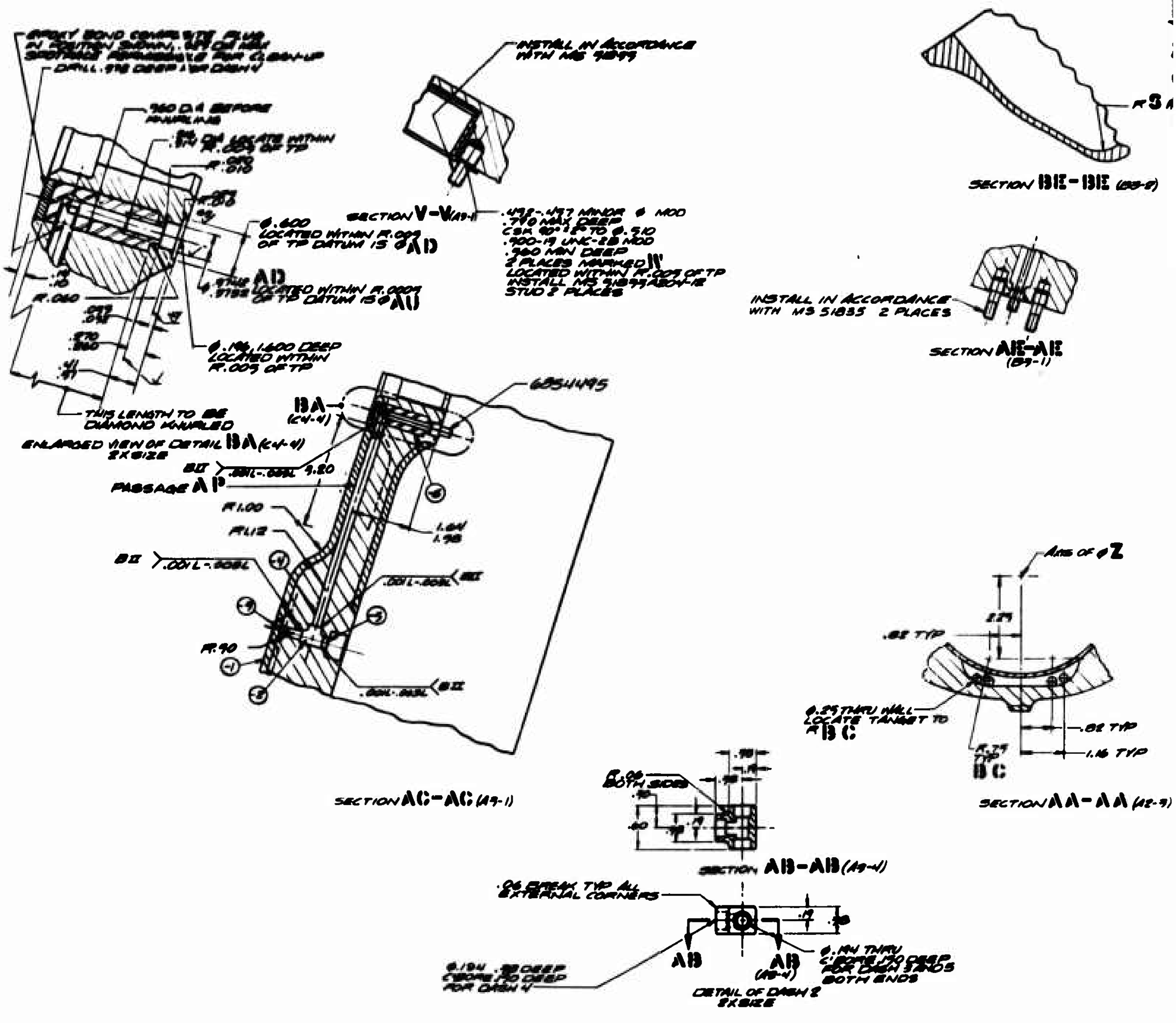



**Figure 3-5. T56-A-18 reduction gear c**

**(Sheet**

A.

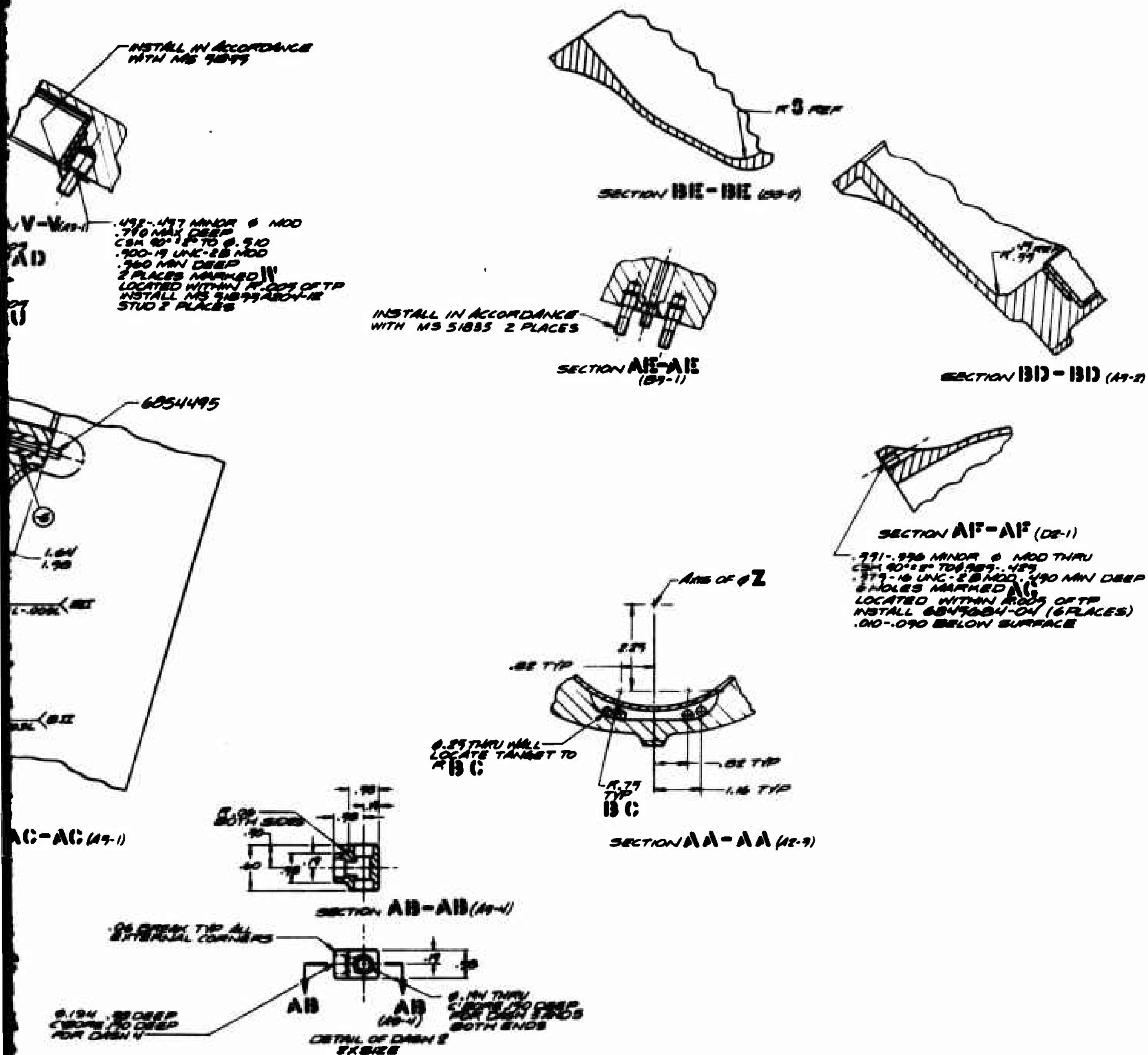


**Figure 3-5. T56-A-18 reduction gear composite material front gear case details.**
**(Sheet 4 of 4)**

Table 3-III.

Properties and composition of boron-glass-epoxy composite.*

**Short fiber boron-glass-epoxy composite**
**(Fiber Length = 1 in.)**

Composition: 2.5 parts by volume of glass-epoxy, 1 part boron-epoxy

Glass/epoxy

- NARMCO 5505 Modified NOVALAC: Epoxy prepreg system**
- Reinforcement: End "S" Glass, 901 Finish Roving
- Resin content: 33% by weight

Boron/epoxy

- NARMCO 5505 Modified NOVALAC: Epoxy prepreg system
- Reinforcement: 26 filaments per 1/8-in. collimated unsupported tape
- Resin content: 33% by weight

Density: 0.077 lb/in.$^3$

| | |
|---|---|
| Thermal expansion (76-300°F) | $1.78 \times 10^{-6}$ /°F |
| Young's modulus (E) | $10 \times 10^6$ psi |
| Poisson's ratio ($\mu$) | 0.30 |
| Tensile ultimate ($F_{TU}$) | 37,500 psi |
| Compressive ultimate ($F_{CU}$) | 45,000 psi |
| Shear ultimate ($F_{SU}$) | 22,500 psi |

**Continuous boron-epoxy composite**

Composition: NARMCO 5505 Modified NOVALAC: Epoxy prepreg system

Reinforcement: 0.004-in. boron filament (208 filaments per inch of ply width)

Glass carrier: Style 104 Scrim Cloth, one sheet per ply

Resin content: 33% by weight

Ply thickness: 0.005 in.

Density: 0.077 lb/in.$^3$

| | |
|---|---|
| Thermal expansion (76-300°F) | $2.30 \times 10^{-6}$ /°F |
| Young's modulus—Longitudinal ($E_L$) | $27.5 \times 10^6$ psi |
| Young's modulus—Transverse ($E_T$) | $3.1 \times 10^6$ psi |
| Torsional modulus (G) | $1.1 \times 10^6$ psi |
| Poisson's ratio ($\mu$) | 0.38 |
| Tensile ultimate—Longitudinal ($F_{TUL}$) | 180,000 psi |
| Tensile ultimate—Transverse ($F_{TUT}$) | 10,000 psi |
| Compressive ultimate—Longitudinal ($F_{CUL}$) | 230,000 psi |
| Compressive ultimate—Transverse ($F_{CUT}$) | 22,500 psi |
| Shear ultimate ($F_{SU}$) | 10,000 psi |

*Strength properties tabulated herein are design values and are conservative because of limited experience with this composite.

**Whittaker Corporation, NARMCO Material Division, Costa Mesa, California

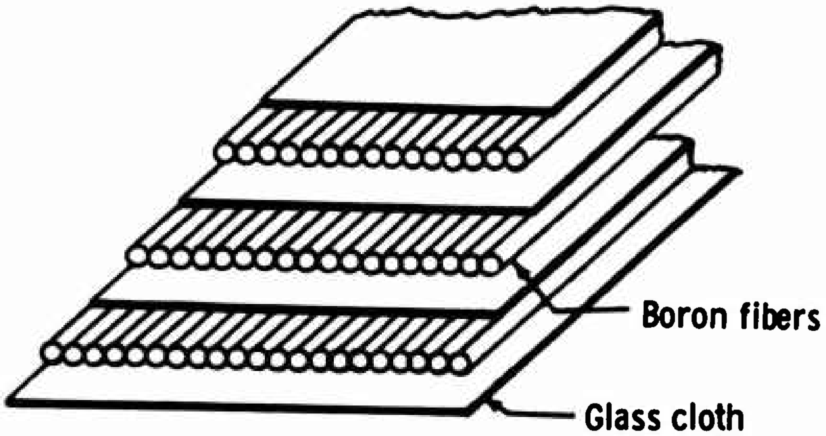



**Figure 3-6. Fiber strips.**

Machining of Composite

A number of machine operations will have to be performed on the composite case after molding and at the present time little information is available on machining of boron-glass-epoxy composite. Goodyear Aerospace Corporation has found that diamond tip drills give good results in drilling operations while excessive tool wear is exhibited by carbide tip drills. Preliminary experiments with tapping the composite have yielded acceptable threads but high tap wear.

It is anticipated that grinding the composite material will be a feasible operation.

Because of the lack of information on machining, every effort was made to minimize machine operations by eliminating unnecessary operations or by molding to finish dimensions. In some areas it was impractical to hold finish tolerances on the molded surface because of shrinkage of the molded part after removal from the mold. In these areas machine operations will be required.

The following principal areas require machining.

- Case flange—it was doubtful that the required flatness and finish could be held on this area in the "as molded" condition.

- Bearing bores—a very close tolerance must be held on the location of these surfaces; the effect of mold shrinkage on locations reduces the confidence in tolerances.
- Oil transfer ports—these must be located quite close, relative to the bearing bores. Again, mold shrinkage introduces an unknown.

## Threaded Fasteners

Threaded fasteners are required in a number of locations on the composite case; both bolts and studs are used. The following schemes were considered for the threaded areas of the case.

- Drill and tap for installation of studs and inserts.
- Mold in studs and inserts.
- Mold in steel blanks in the locations where studs and inserts are required, then drill and tap in the steel after molding.

The use of molded in studs and inserts was desirable from the standpoint that machine operations would be reduced in the finished part. However, this technique was impractical because close tolerances are necessary on the insert locations; it would be necessary to know the exact effect of mold shrinkage to obtain the required tolerance on location.

Molded in steel blanks are feasible and would allow close tolerances on the fastener location. A problem with this approach would occur if the blanks worked loose in the mold or if overhaul rework were required. At this point the repair process would require drilling out the inserts and either bonding in new blanks or tapping and installing threaded inserts. Although this method could probably have been developed, it was felt to have excessive risk for this particular program. The method finally selected was to drill and tap the composite, then install inserts and studs.

## Placement of Material

The front case of the T56-A-18 reduction gear assembly is required to react bending moments in both the front wall and side area. Radial ribs are an integral part of this design. The ribs react the bending loads with a minimum amount of material and a maximum of stiffness.

The ribbed area was felt to be an excellent place to make use of the high longitudinal modulus of the continuous filament composite. Figure 3-7 shows where the continuous filaments are placed to increase the stiffness of the ribs.

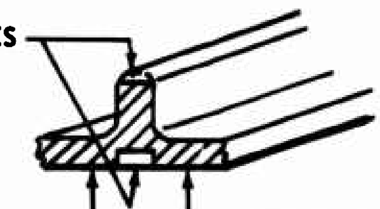



**Figure 3-7. Cross section through typical radial rib.**

The bearing reactions from the main drive and pinion gears act in a direction that tends to separate these two bearing bores. A minimum separation in this area is desirable for reduction of bearing and gear misalignment. To counteract these forces, additional material was added between the bearing bores. This material was added in the form of ribs tangential to the two bearing bores. See Figure 3-8.

A collar of wound, continuous filaments was molded in the case around the pinion bore. The function of this collar is to distribute the point load from the pinion to the face of the front case. Distribution of this load is by tensile forces in the collar and shear forces at the interface of the collar and case structure. Figure 3-9 shows this collar.

The ends of all continuous filament strips were tapered so that abrupt changes in load transmission did not occur.

Thermal Considerations

A typical aircraft reduction gear assembly application would require operation over a wide range of temperature from cold starts at -65°F up to a maximum operating temperature of 300°F. Where the reduction gear cases are all one material the case components can expand and contract uniformly without introducing internal stress. This is not true when a composite front case is assembled to a magnesium diaphragm and rear case and steel bearing rings. Thermal expansion coefficients for boron-glass-epoxy resin composite and magnesium are quite different; if the composite/magnesium reduction gear assembly were operated over a wide range of temperature, fairly large thermal stresses would occur. Refer to the subsection entitled Thermal Stress and Table 3-IV.

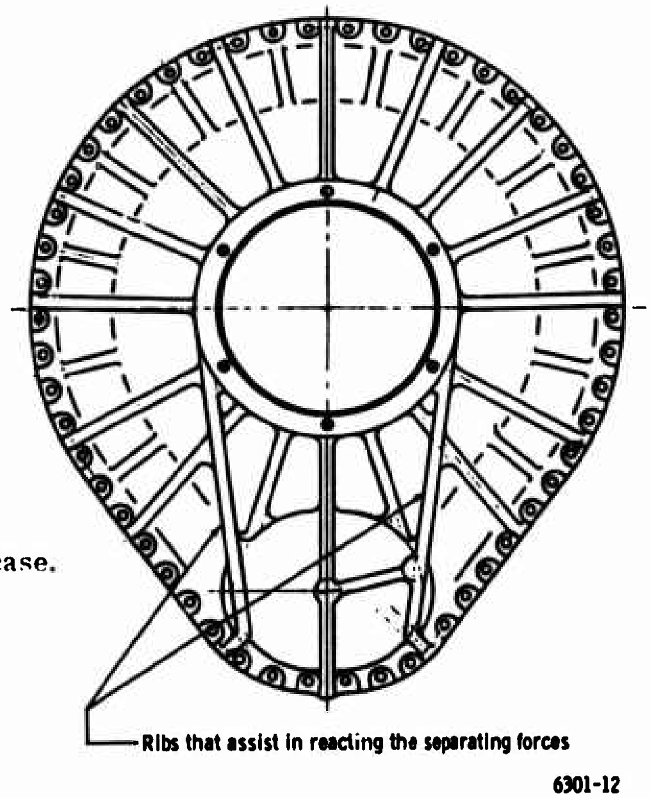



Figure 3-8. Front view of composite gear case.

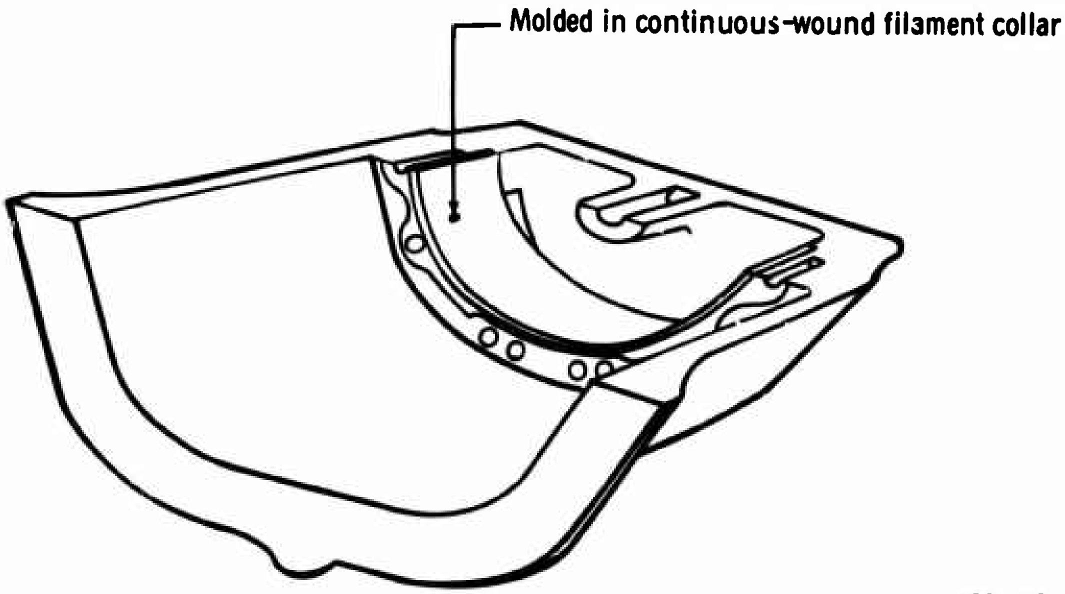



Figure 3-9. Cr - section through reduction gear pinion bore.

Table 3-IV.
Thermal coefficients.

($\times 10^{-6}$ in./in. °F)

| | |
|---|---|
| Magnesium | 14 |
| Short fiber composite | 1.78 |
| Continuous fiber composite | 2.3 |

The preliminary stress analysis predicted excessive stresses if a solid joint at the front case to diaphragm flange was used. The following alternatives were available to avoid this problem.

- Redesign the flange area and diaphragm to allow for differential radial expansion.
- Avoid operation over a wide range of temperature.

A redesign of the flange area would have been costly and would not have helped to achieve the main objective of the program, i.e., a feasibility demonstration of composite material. When the use of composite material has been demonstrated to be feasible, reduction gear assemblies fabricated from such material would be all composite and would not suffer from thermal expansion problems. For the previously discussed reasons, the operating temperature of this demonstration case would be restricted to the possible minimum and would not exceed 150°F in any event.

The fit between bearing races and the front case was selected so that at 150°F the interference fit would not cause an excessive amount of reduction in the internal clearance of the bearings. These factors were carefully considered because the steel races expand at approximately three times the rate of the composite case.

## Oil Passages

The front case picks up oil at one point and distributes the oil through tubes to two locations for lubrication and cooling. For this purpose oil tubes were designed to be molded integrally with the case. The tubes are stainless steel with brazed fittings. Design of the tubes is such that they can be located by the mold dies during the molding process. See Figure 3-10.

Molding in of the oil tubes represented one area of risk that was not felt to be of sufficient importance to compromise the overall case design. Design flexibility permitted the use of external lines if difficulty was experienced in molding the integral oil tubes.

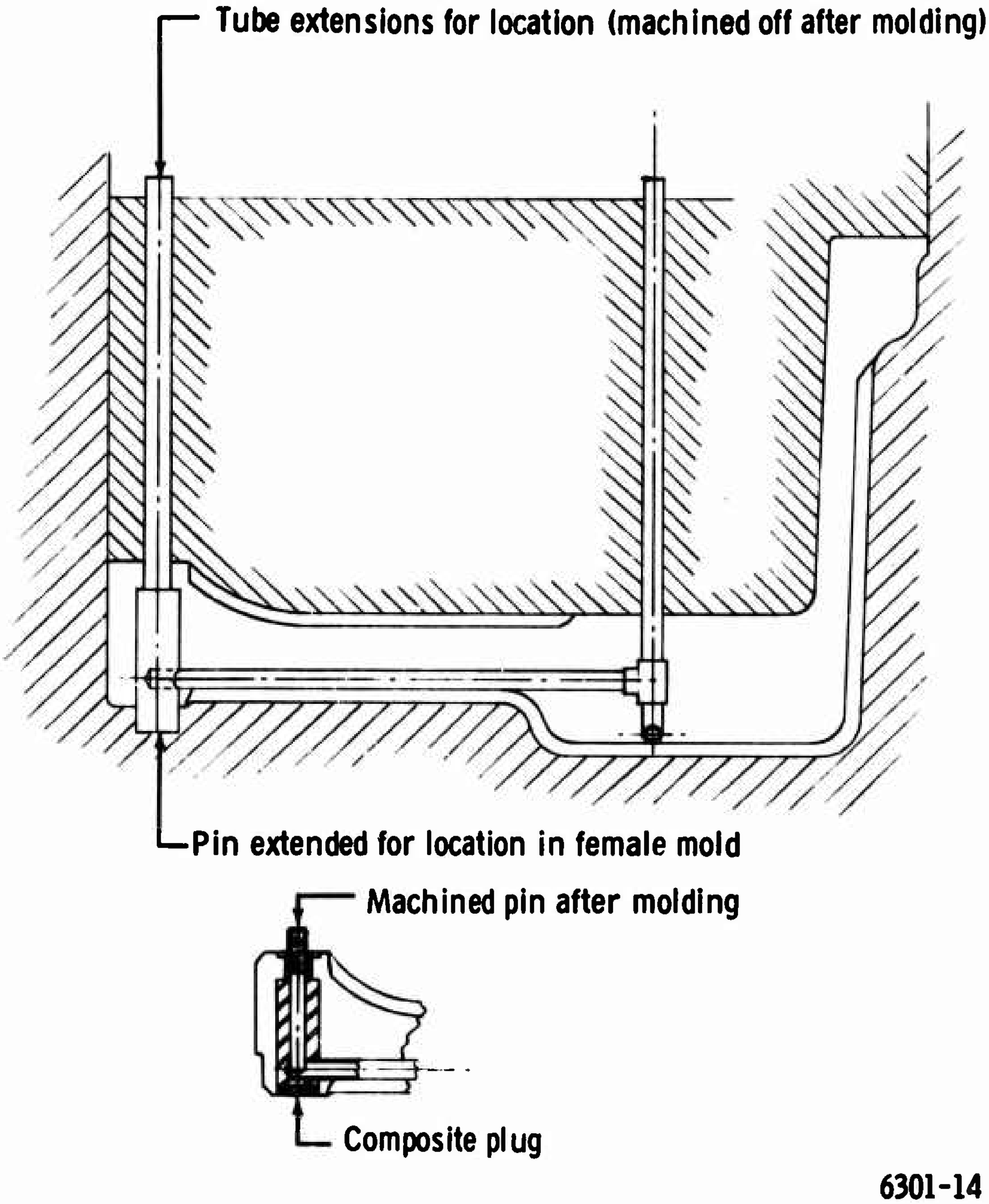



Figure 3-10. Locating oil tubes in mold.

### Case Envelope

The dimensions of the composite case envelope have been held within the dimensions of the original magnesium case envelope to avoid interference with other components. Clearance has also been retained for the propeller mechanism and spinner.

### Propeller Orientation

The T56-A-18 reduction gear assembly was originally designed to operate with the input pinion above the propeller shaft. During the T56-A-18 program a change was made to re-orient the input pinion below the propeller shaft. As a result, the front T56-A-18 magnesium case had bearing and seal oil drains for each mode of operation. The oil drains for pinion-high operation have been eliminated in the composite front case design to reduce machining operations.

### Composite Case Weight

A preliminary weight estimate was prepared for the composite front gear case. The following estimate was based on Allison P/N AL-17129 (Figure 3-4) and shows a weight reduction of 13% when compared to the magnesium front gear case, Allison P/N 6858781.

- Magnesium case weight 32.94 lb
- Composite case weight 28.58 lb

## STRESS AND DEFLECTION ANALYSIS

The following paragraphs discuss the stress analysis performance during the composite front case design.

### Thermal Stress

In a turboprop application the composite front gear case could be bathed by oil at temperatures as high as 300°F. This would result in differential thermal growth of the front case relative to a magnesium diaphragm. Evaluation of the stress level in the front case as a result of differential thermal growth would also be possible. See Figure 3-11.

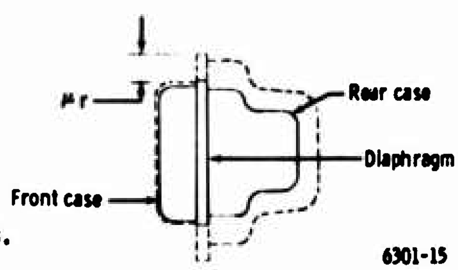



Figure 3-11. Thermal growth of gear case components.

As noted previously, the difference in thermal expansion coefficients for magnesium and composite is on the order of $12.0 \times 10^{-6}$ in./in. °F and the radius of the bolt circle at which the expansion occurs is 11.75 in. The differential thermal growth ($\mu_r$) is:

$$\mu_r = 12 \times 10^{-6} \, (230°F) \times 11.75$$
$$\mu_r = 0.0324 \text{ in.}/°F$$

The conservative assumption is that the composite case would be subjected to the full radial expansion of 0.0324 in./°F.

This radially displaced condition was analyzed by an Allison shell analysis program (AS08). A cone-and-disk element was used to approximate the gear case and the stresses were calculated as a function of the material modulus. The stresses in the tangential ($\sigma_t$) and meridional ($\sigma_m$) directions (Figure 3-12) were far in excess of the design allowables in the region close to a radial displacement equivalent to $\mu_r$. Stresses are shown in Figures 3-13 and 3-14.

These stresses, $\sigma_t$ and $\sigma_m$, are about twice the ultimate strength of 37,500 psi for the short fiber boron-glass-epoxy composite. Although the stresses quickly attenuate, the operating temperature of a composite/magnesium reduction gear assembly must be restricted to as low a level as possible.

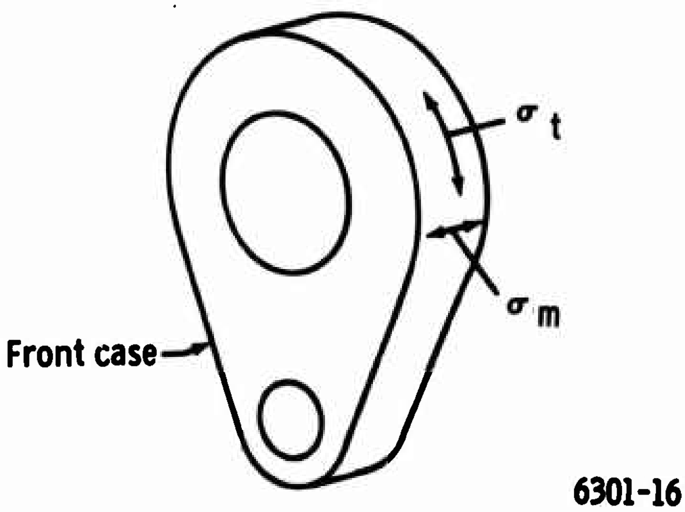



**Figure 3-12. Tangential and meridional stress in front gear case.**

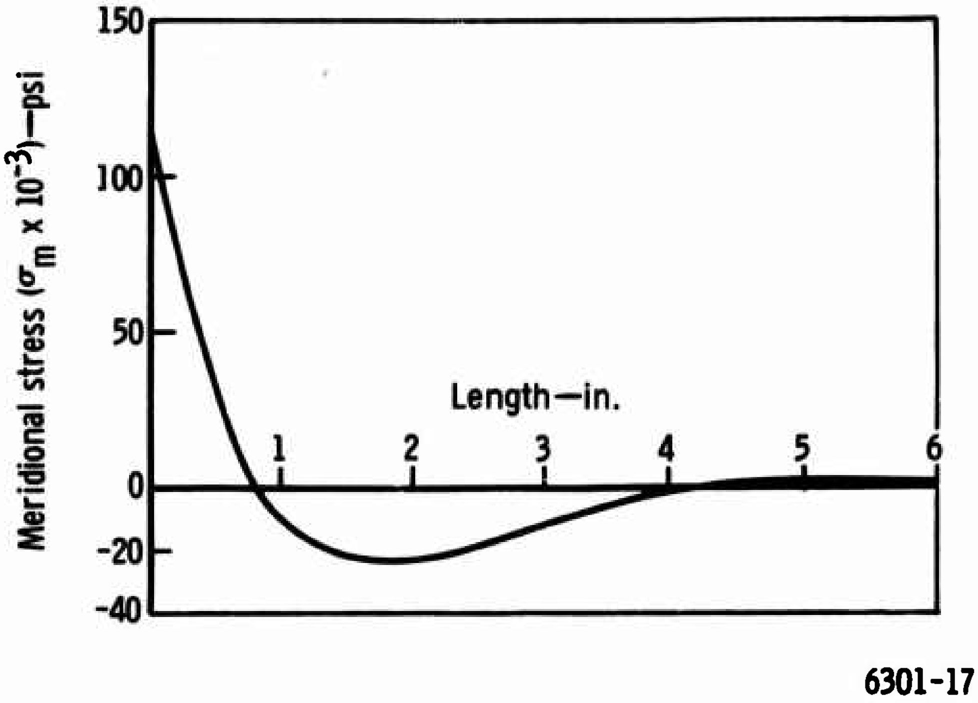



Figure 3-13. Meridional stresses versus shell length.

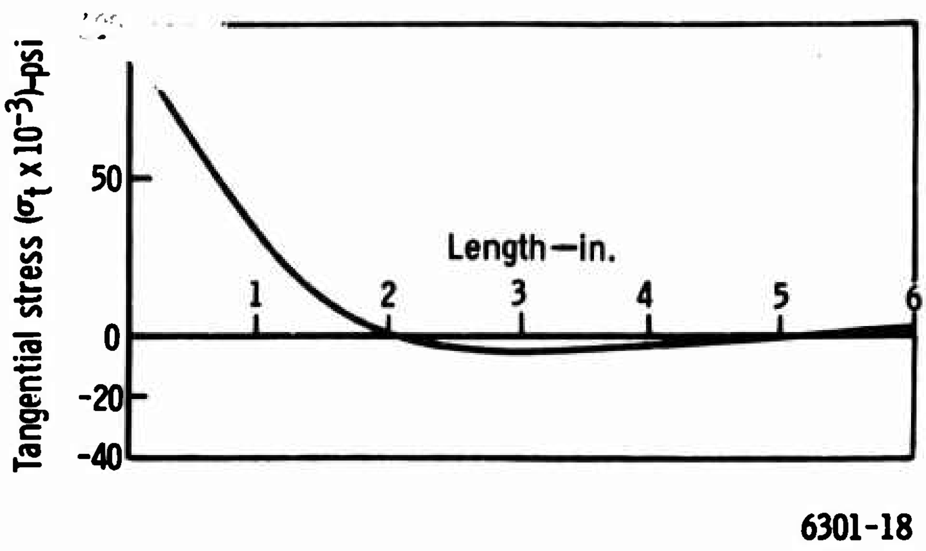



Figure 3-14. Tangential stress versus shell length.

Deflection Analysis

The composite front gear case was designed for a specific level of deflection under the loads detailed in the previous subsection, Design Requirements.

The most severe load of those noted is the load induced by the main drive gear bearing. This load produces a moment on the case which, in turn, creates significant deflections in the front case face. Resultant deflection data obtained during extensive static testing of the T56-A-18 magnesium front case under the moment load were applied to the design of the composite case.

The approach taken for the composite case deflection analysis was that of establishing an initial configuration and then analyzing the deflections caused by load. The case configuration was extrapolated from the magnesium case design by an equivalent section method. Each section of the case was envisioned as supporting a load in bending. Section stiffness of the initial composite case concept was designed to be same as the magnesium case by proportioning the product of material modulus (E) and the moment of inertia (I). Letting subscript m refer to magnesium and subscript c refer to composite, the basis of establishment for the initial composite case configuration can be defined as

$$E_m I_m = E_c I_c \qquad (1)$$

The modulii are:

$E_m = 6.5 \times 10^6$ lb/in.$^2$

$E_c = 10.0 \times 10^6$ lb/in.$^2$

Then from Equation (1) and the material properties:

$$\frac{I_m}{I_c} = \frac{E_c}{E_m} = \frac{10.0}{6.5} \qquad (2)$$

Each section of the case was considered as a rectangular section; therefore, the moment of inertia (I) for a rectangular section is:

$$I = \frac{1}{12} b\, t^3 \qquad (3)$$

where:

b = base = 1 (unit width)

and:

t = section thickness

$$I = \frac{t^3}{12} \tag{4}$$

substituting (4) into (2):

$$\frac{t_m^{\ 3}}{t_c} = \frac{10.0}{6.5}$$

or:

$$\frac{t_m}{t_c} = 1.155$$

or:

$$t_c = 0.868\ t_m \tag{5}$$

For each section of the composite case, the thickness was initially set at 87% of the corresponding section of the magnesium case.

After preliminary sizing by the described method, an Allison finite element plate and beam analysis program was used to predict the deflection characteristics of the case.

Figure 3-15 shows the basic analytical and numerical methods for structural stress analysis and the division of specific techniques under the numerical method.

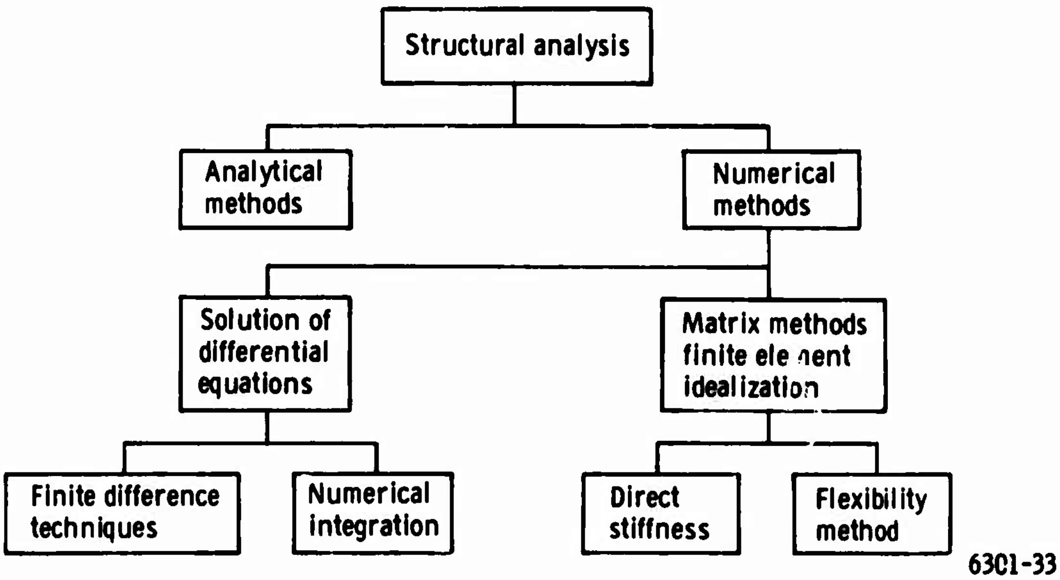



Figure 3-15. Methods of structural analysis.

The direct stiffness method was selected for analysis of the composite gear case for the following reasons.

- Analytic solution of differential equations is restricted to simple structural configurations.
- Matrix methods are ideally suited for such complex structural configurations as the composite case and can be formulated for solution on a digital computer.
- Allison has experience with the direct stiffness method and a library of stiffness matrices for use with computer solutions.

The direct stiffness method yields the following results:

- Stresses
- Deflections
- Natural frequencies
- Forced vibration response at selected points defined as nodes

Analysis of a complex structure by the direct stiffness method requires that the structure be modeled as a discrete number of simple structural elements connected at the nodes. Figure 3-16 is an example of the analysis of a simple, rib-stiffened cantilevered plate for which a simple handbook solution is not available.

The finite element model for solution by the direct stiffness method would appear as shown in Figure 3-17.

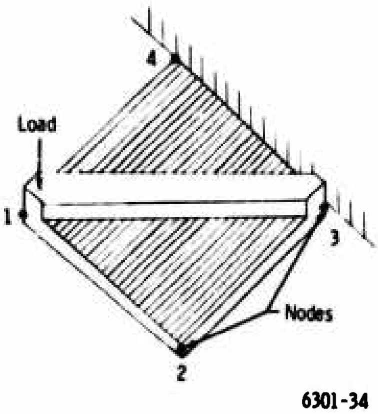



Figure 3-16. Rib-stiffened cantilevered plate.

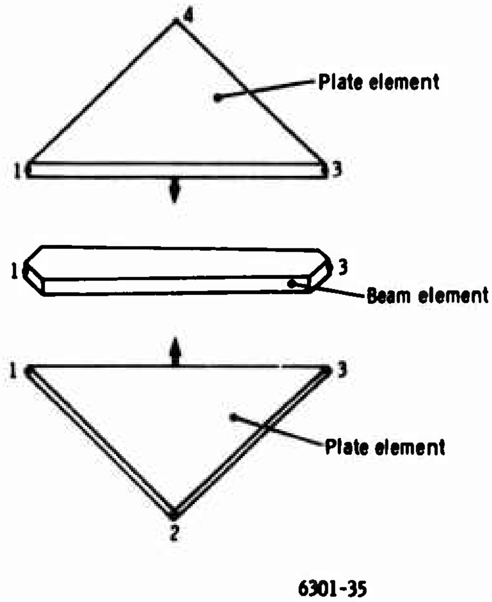



Figure 3-17. Model of rib-stiffened plate.

Once the structure is broken up into elements that can be analyzed, a stiffness matrix that describes the force deflection properties of each element is prepared. Consider the case of a simple tension/compression bar. See Figure 3-18.

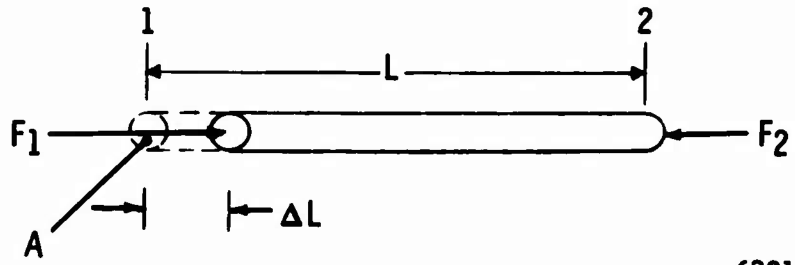



**Figure 3-18. Tension/compression bar.**

The equations for the tension/compression bar would be:

$$\sigma = E\epsilon$$

$$\sigma = F/A$$

$$\epsilon = \frac{\Delta L}{L}$$

$$F/A = E\frac{\Delta L}{L}$$

$$F = \frac{AE}{L}\Delta L$$

L = Length
$\sigma$ = Stress
E = Modulus of rigidity
$\epsilon$ = Strain
F = Force
A = Area
K = Spring rate
$\delta$ = Deflection

For stiffness formulation:

$$F = K\delta$$

$$K = \frac{AE}{L}$$

When writing the force-deflection equations in matrix form:

$$\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 \\ 0 & \frac{-AE}{L} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix}$$

The matrix $\begin{bmatrix} \frac{AE}{L} & 0 \\ 0 & \frac{-AE}{L} \end{bmatrix}$ is defined as the element stiffness matrix. The calculation of stiffness matrices for many different elements is the central problem of the direct stiffness method.

The element stiffness matrices, which can be thought of as building blocks, are assembled according to the rules of equilibrium and compatibility to form force-deflection properties for the actual complex structure.

Confidence in this method was established by a finite element analysis of the T56-A-18 magnesium case for which existing deflection test data were available. The analysis predicted front case face average deflections within 10% of those measured during testing.

Having established confidence in the available analytical tools, the finite element method was applied to the composite front gear case. Figure 3-19 shows how the composite case structure was broken into a number of simple elements. Each element was described by stiffness matrices and a computer program (Allison Program BC15) was used to assemble a complete description of the case structure. Deflections and stresses were determined for each node after boundary conditions and external loads were applied.

The initial results for the composite case indicated that an excessive slope would occur at the pinion face on this case also. Additional ribs were added in the pinion area and the case was analyzed again. After a number of iterations (during which time rib sizes were adjusted) a satisfactory result was achieved. Front face deflections were reduced and the pinion bore area did not exhibit excessive deflections.

The front face deflection for the final result is shown in Figure 3-20. It will be observed that the predicted slope of the composite case is one-half that measured in test of the magnesium case. This represents a significant increase in stiffness of the front case. The effect of reduced deflections on reduction gear internal rotating hardware could only be beneficial.

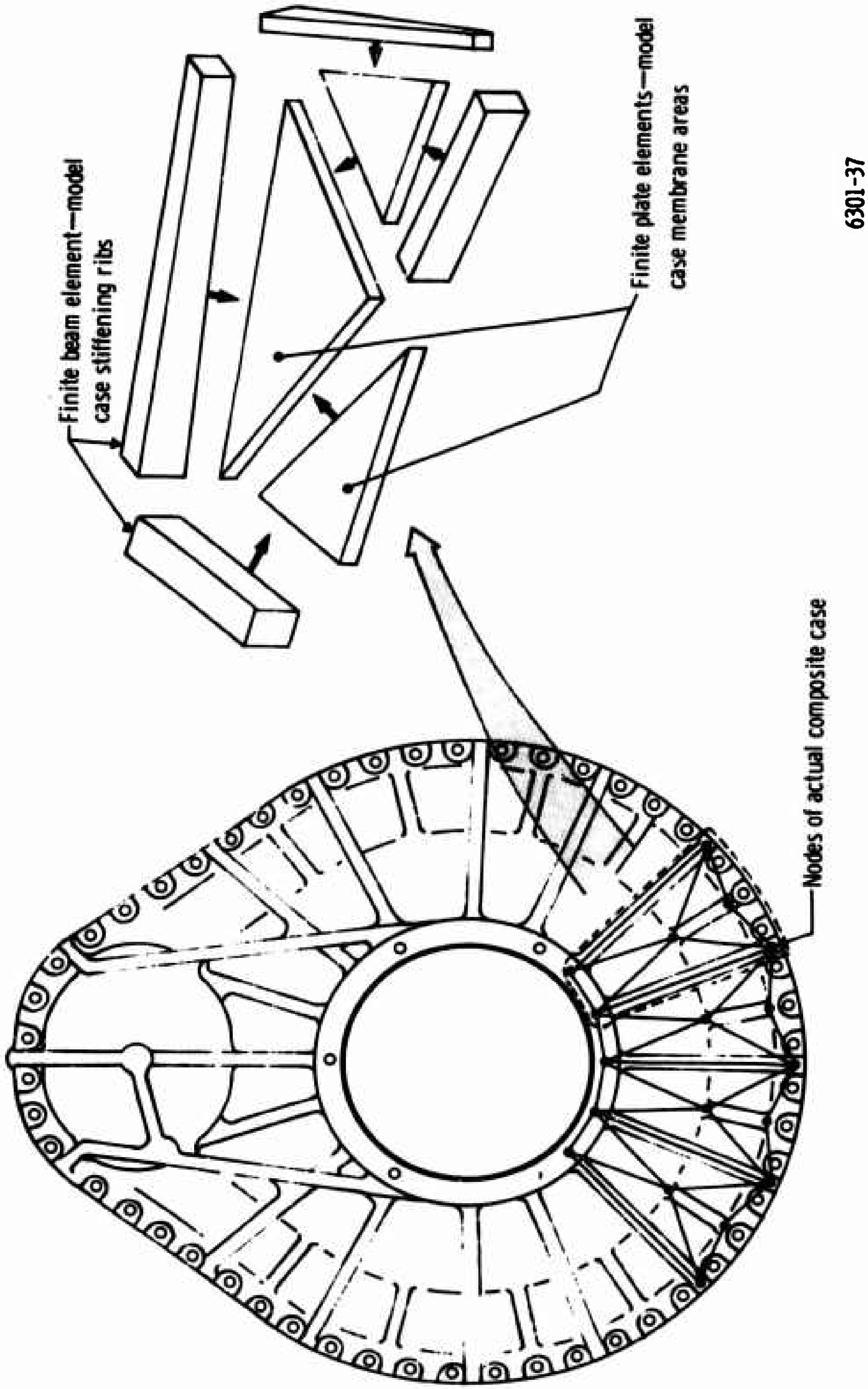



Figure 3-19. Finite element idealization of composite case.

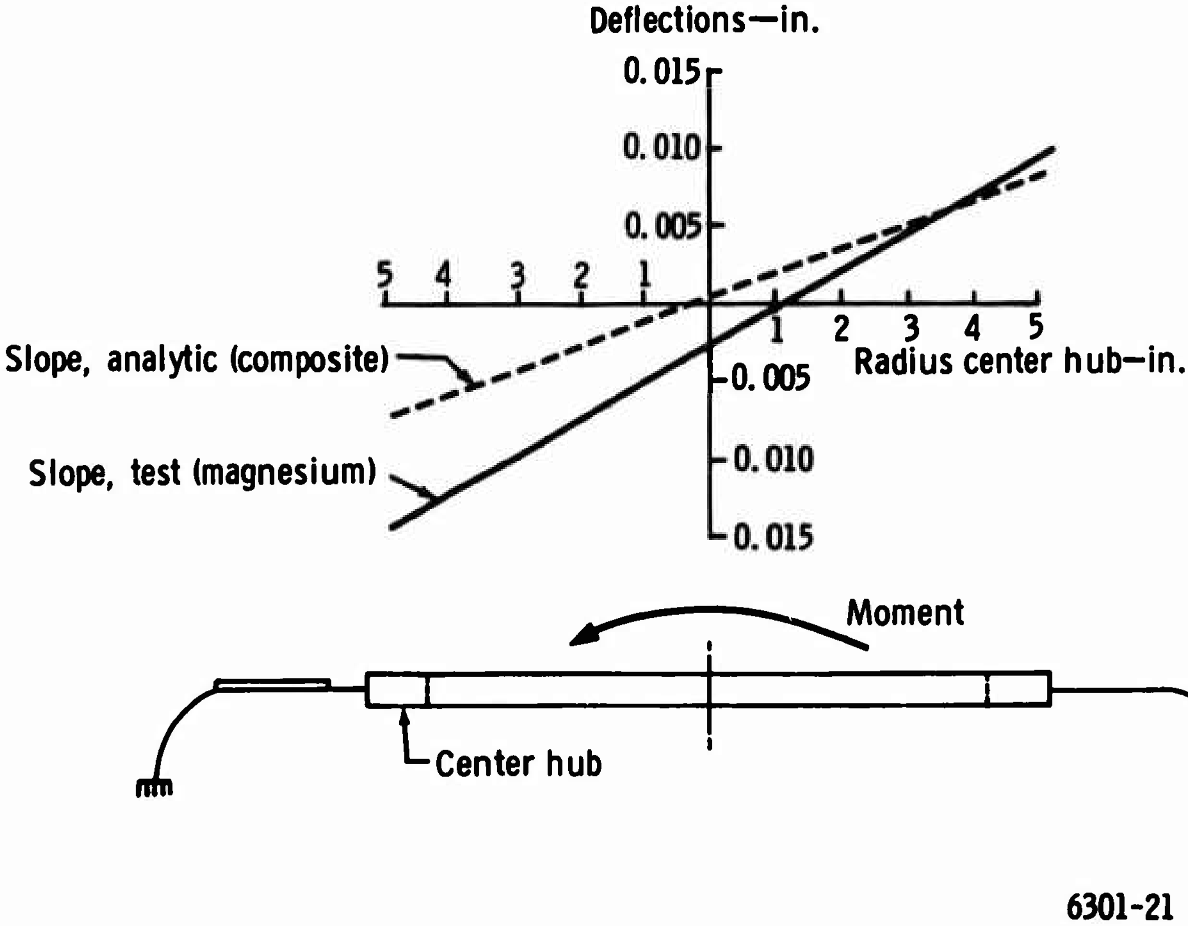



**Figure 3-20. Comparison of magnesium and composite case deflections.**

# IV. MOLD FABRICATION

## TOOLING

One female and two male matched metal dies were machined for process molding the composite front gear case. Die machining was subcontracted by Goodyear Aerospace to Mechanical Mold and Machine Company, Akron, Ohio. Details, which appear in Figure 3-5 (Allison Drawing EX-92493), prescribed mold configuration, tolerances, and draft angles to which the tool design drawing (Mechanical Mold Drawing No. 68-1339) was generated. See Figures 4-1 through 4-5. The female mold, representing the outside surface of the case, is common to both male molds. Figure 4-6 illustrates the female mold and shows the recessed areas for placement of external stiffener unidirectional filaments. The first male mold, Figure 4-7, is constructed with ribs for molding recessed areas on the inner surface to permit placement of internal stiffener unidirectional filaments. The second male mold is similar to the first except for a smooth exterior surface and its programmed function was to mold the internal stiffener filaments in the recessed areas formed by the first male mold. A change in processing, whereby the second male mold was eliminated from final composite molding, is explained in the following subsection, Tool Tryout.

High molding pressures and curing temperatures determined the selection of matched mold metallurgy. All molds were surface polished, cored for steam heating, and incorporated stops to aid in the control of part thicknesses prescribed by specifications.

## TOOL TRYOUT

A material survey was conducted in conjunction with tool tryout prior to composite molding. Four molds were processed to survey material flow characteristics, shrinkage, and processing procedures. A definition of the materials and the basis for their selection in processing the four tryout molds follows.

- Two units were molded using Diallyl Pthalate molding compound. This material is generally used for mold tryout because of its free-flowing characteristics.
- One unit was molded, using 3M 1157 epoxy molding compound. This material was selected because of its minimal flow characteristics.
- One unit was molded using Narmco 5505 modified epoxy resin impregnated into glass roving. This material was selected because of its properties similarities to boron-glass-epoxy permitted verification of time-temperature curing cycles.

The first two tryout units processed required the use of 27 lb of Diallyl Pthalate. After placement of the compound in the female mold and press closing with the first male mold, the parts were cured for 2 hr at 270°F under 2000 psi pressure. Examination after molding showed an approximate part shrinkage of 0.003 in./in. Displacement of four 0.250-in. dia pins that form the pinion gear scavenge oil passages was noted and attributed to high material flow pressures. The molded passages were deleted and the scavenge holes were left to be machine drilled in the molded part.

The 3M 1157 compound unit was processed by weighing out 30 lb of material and weight distributing the compound to make a preform representing the configuration of the molded part. After placement of the preform in the female mold and press closing with the first male mold, the part was cured for 2 hr at 290°F and 2000 psi pressure. Shrinkage of the part was approximately 0.001 in./in. The experienced shrinkage rate resulted in the preform approach being accepted for final processing.

The Narmco 5505 preimpregnated glass fiber unit was processed by precisely positioning and preforming 29.49 lb of material as shown in Figure 4-8. This unit featured the initial installation of oil transfer tubes as part of the preform. The preform was densified prior to placement in the female mold. Curing took place for 5 hr at 320°F under 2000 psi pressure. Examination of the unit showed the shrinkage to be approximately 0.001 in./in. and the oil tube assembly was bent out of position. The oil tube assembly missed the alignment hole when mating with the first male mold.

Minor abrasions on the inner wall were blended prior to placement of reinforcement unidirectional preimpregnated glass rovings in the recessed stiffener areas. The reinforcements were cured with the second male mold for 2 hr at 290°F under 2000 psi pressure.

Inspection after curing revealed that some of the reinforcements on the vertical walls of the inner surface slipped out of position during the final closing cycle of the press. To prevent reoccurrence, a change in processing was initiated to replace the second male press with a vacuum bag.

COMPOSITE MOLDING

The first boron-glass-epoxy composite case was processed, using 29.49 lb of the compound. Positioning of the compound was in accordance with the weight sheet shown in Figure 4-8. Preform details, such as filament orientation and the lubrication tube assembly position, are shown in Figures 4-9 and 4-10. Curing of the preform in the female mold, using the first male mold for press, was at 340°F and 2600 psi pressure for 5 hr.

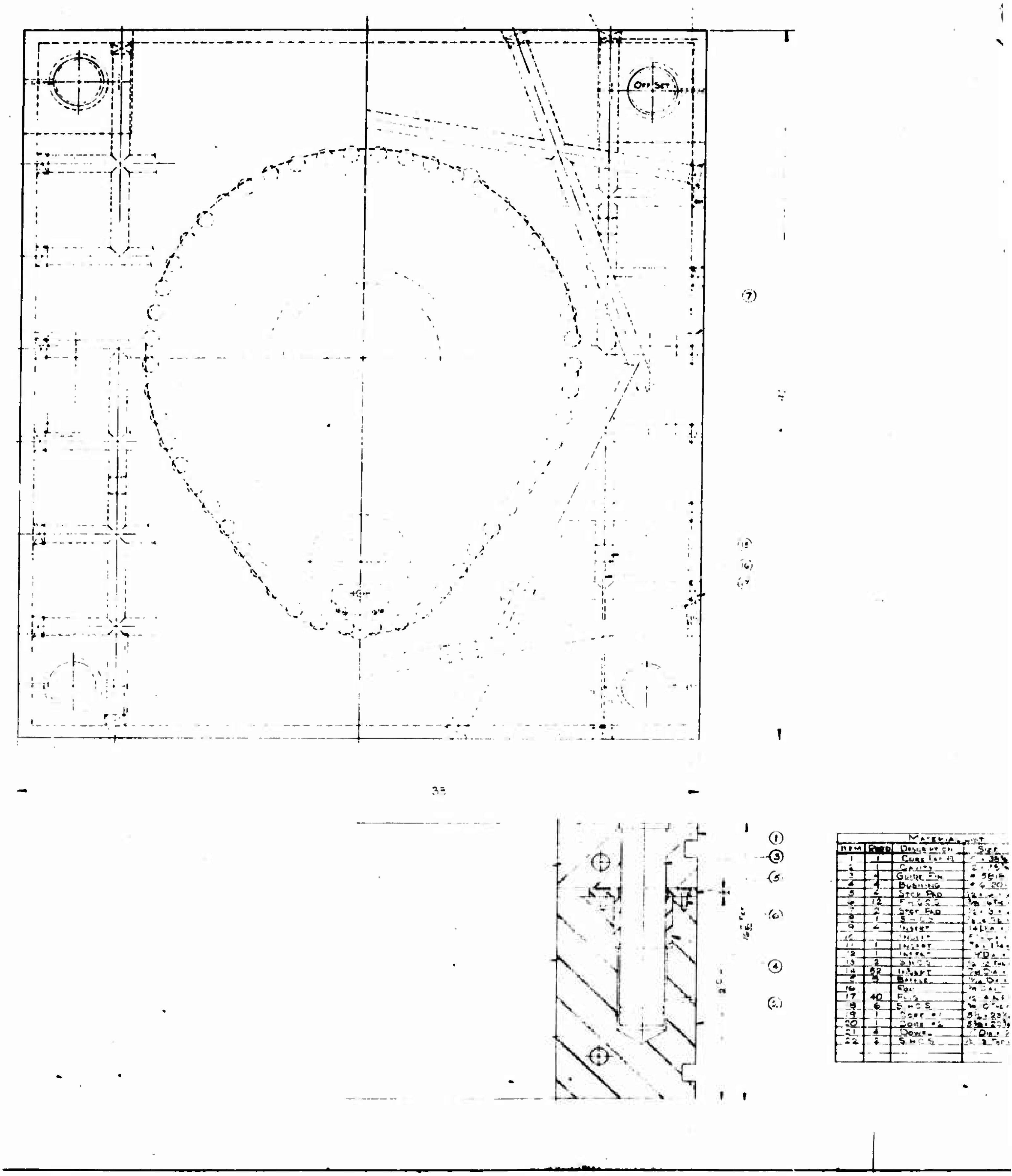



**Figure 4-1. Composite fron**

A1

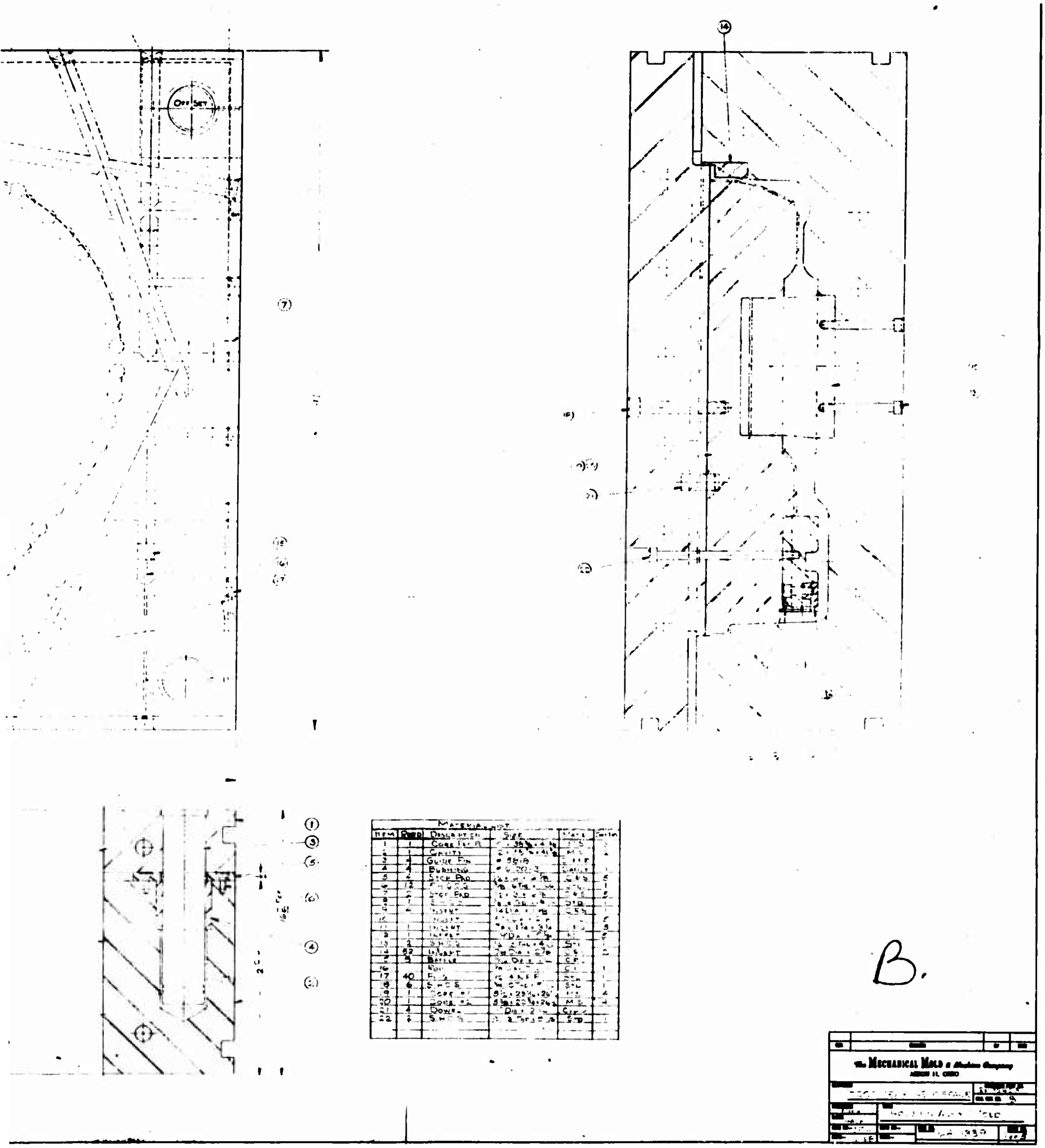
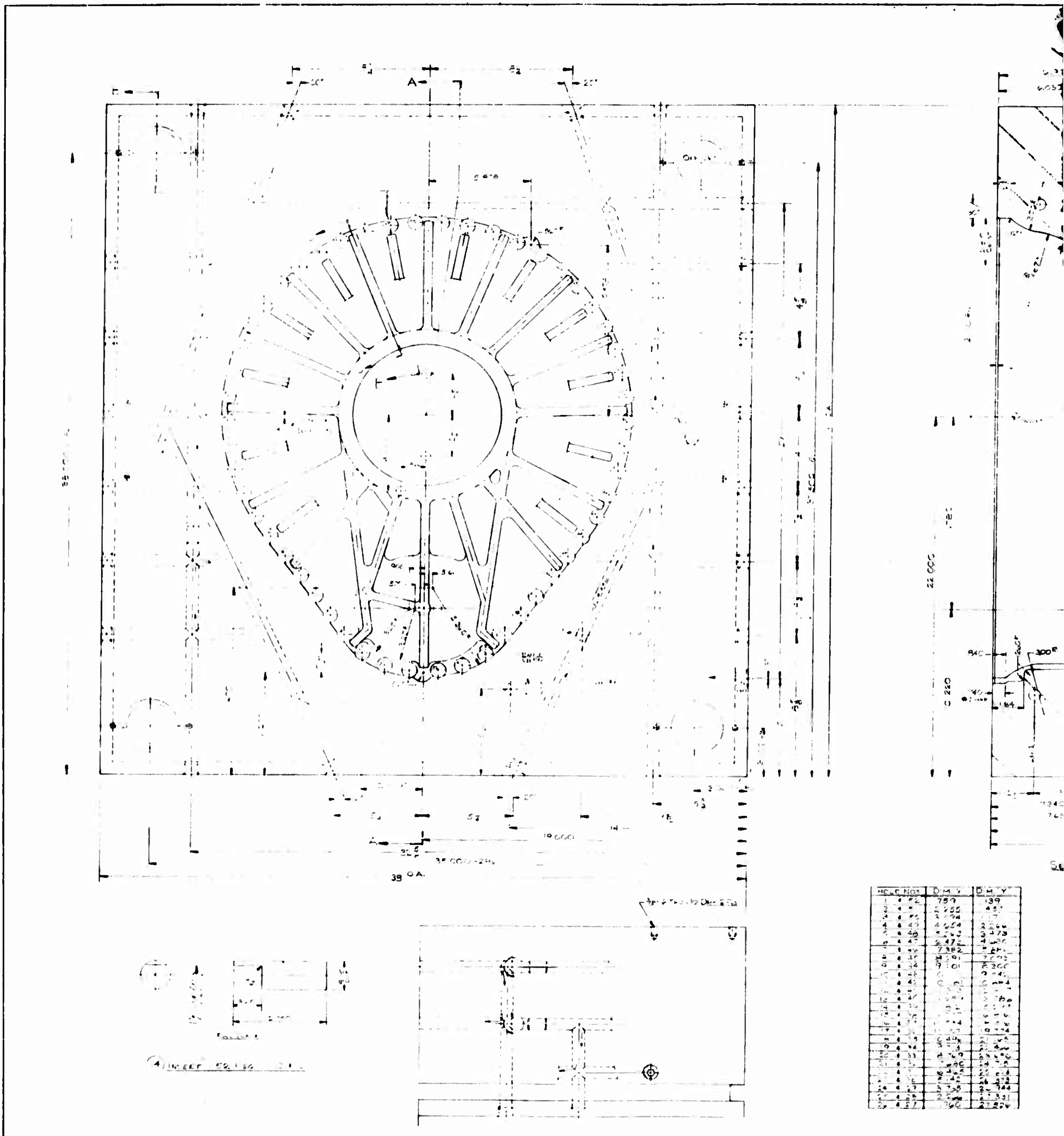



**Figure 4-1. Composite front case mold.**



| HOLE NO'S | DIM X | DIM Y |
|---|---|---|
| 1 [illegible] | 759 | 139 |
| 2 [illegible] | [illegible] | [illegible] |
| 3 [illegible] | [illegible] | [illegible] |
| 4 [illegible] | [illegible] | [illegible] |
| 5 [illegible] | [illegible] | [illegible] |
| 6 [illegible] | [illegible] | [illegible] |
| [illegible] | 7.382 | [illegible] |
| [illegible] | [illegible] | [illegible] |
| 9 [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |

A.

**Figure 4-2. Composite front**

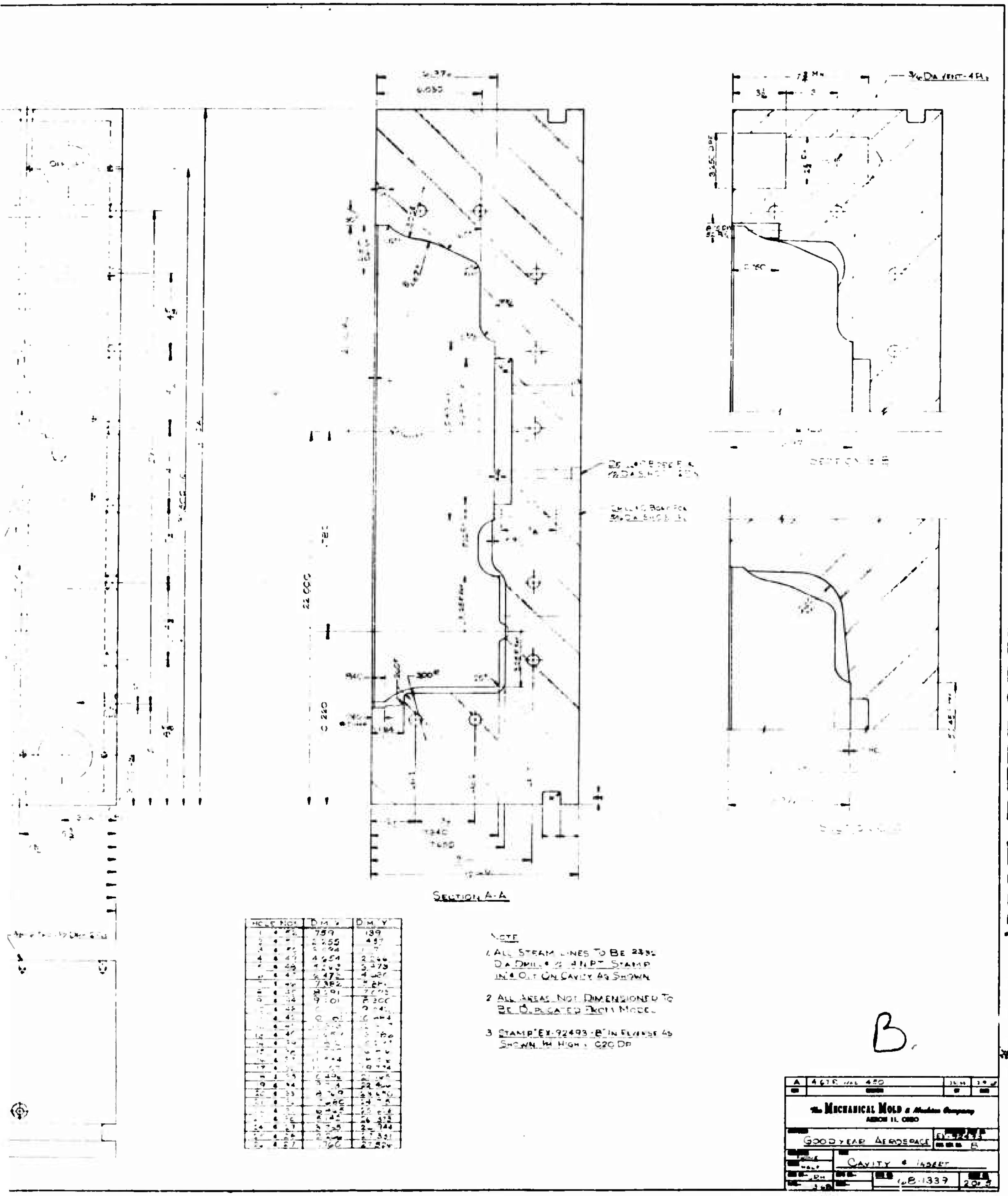
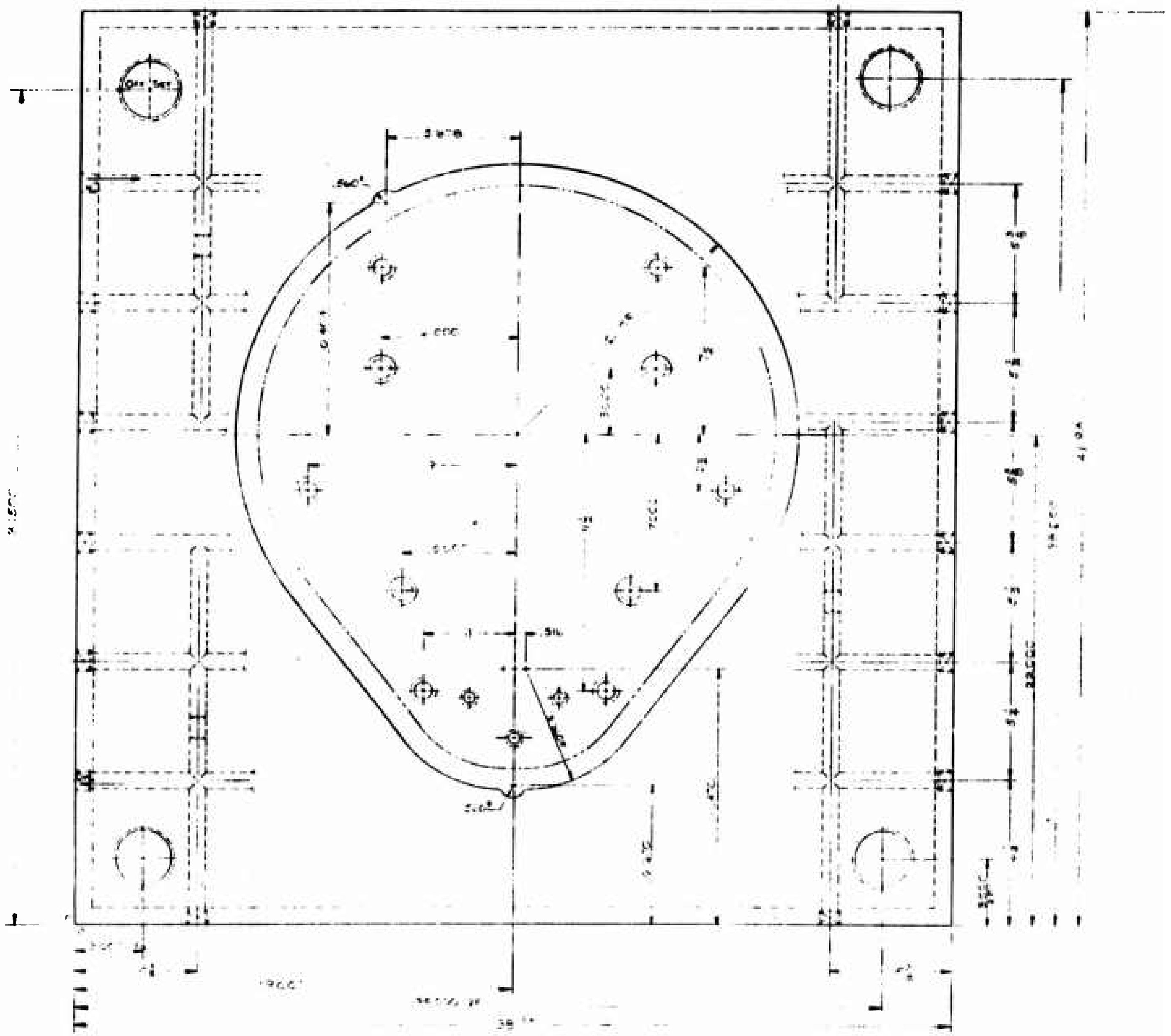





**Figure 4-2. Composite front case mold cavity showing inserts installed.**



(1) CORE RET PL - 1 REQ'D - M.S

A.

Figure 4-3. Co

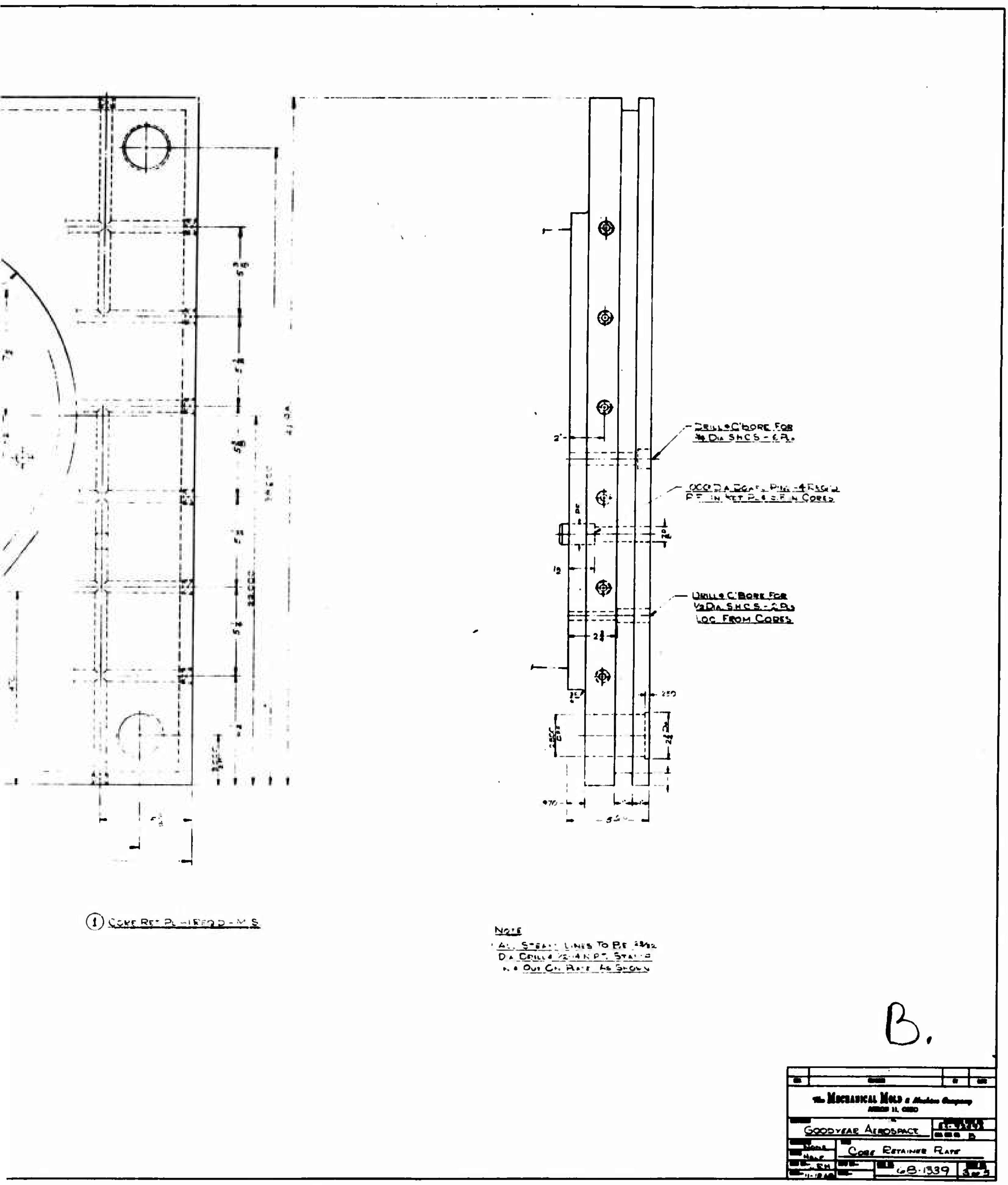
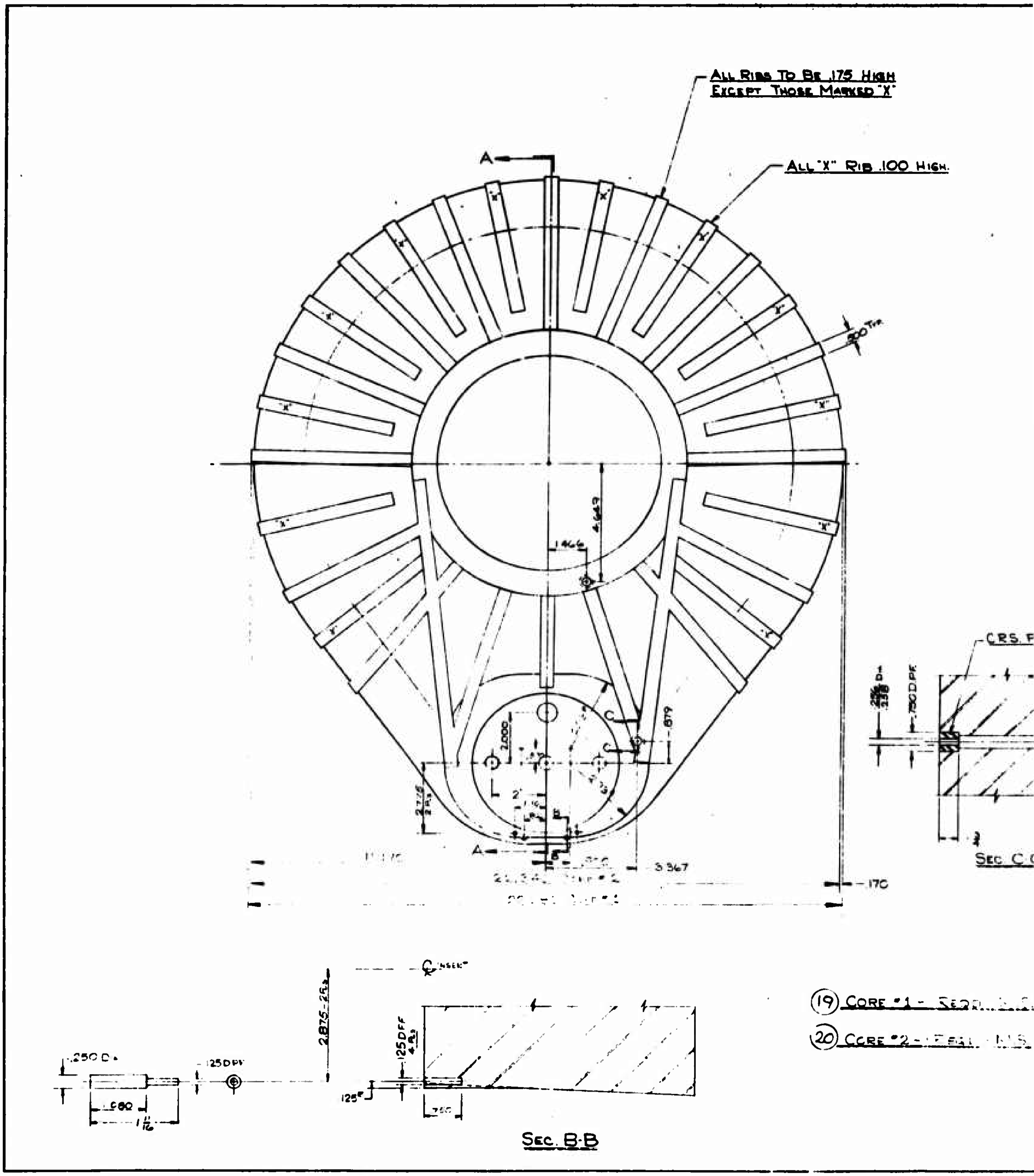


**Figure 4-3. Composite front case mold core retainer plate.**



ALL RIBS TO BE .175 HIGH
EXCEPT THOSE MARKED "X"
ALL "X" RIB .100 HIGH.
.500 TYP.
A
C
4.667
1.466
.879
2.000
3.367
.170
.750 D.P.K.
SEC. B-B
.125 DFF
2.875
.125 DRY
.250 D.
.680
1 1/16
(19) CORE #1 -
(20) CORE #2 -


A.

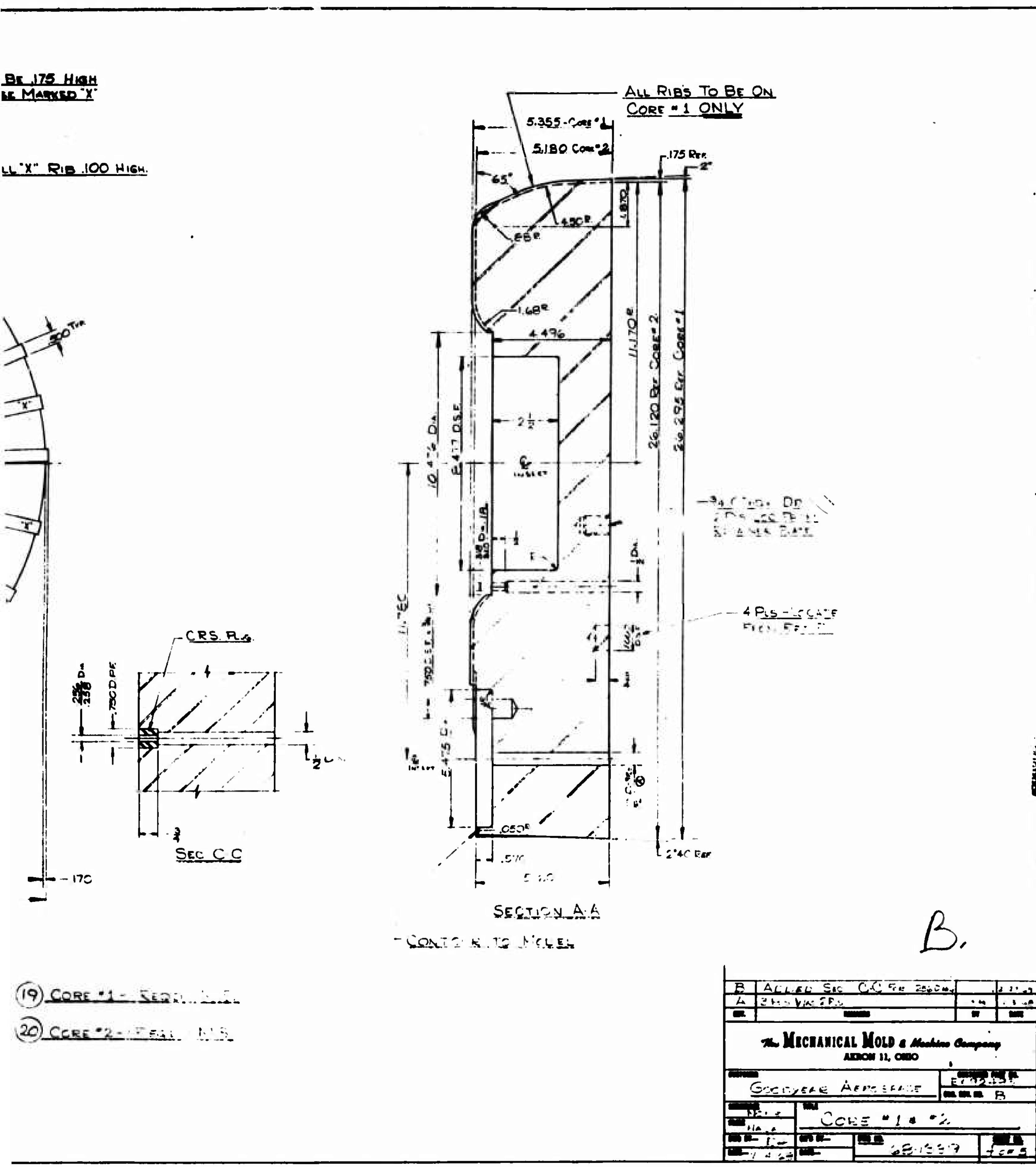
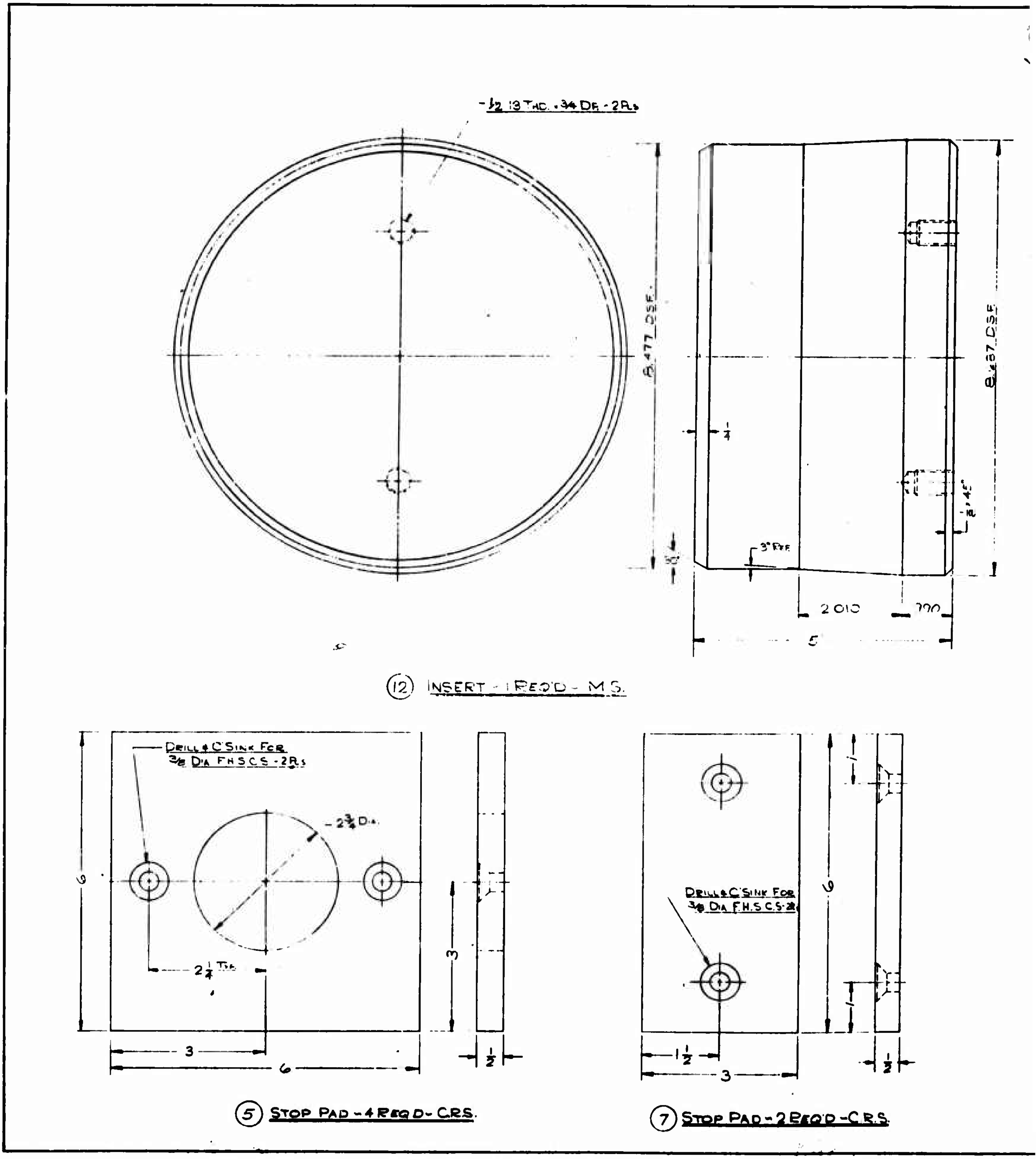



**Figure 4-4. Composite front case mold cores.**



1/2 13 THD. - 3/4 DP. - 2 Rs
8.477 DSF
8.487 DSF
1/4
3° REF
30°
2.010
5
(12) INSERT - 1 REQ'D - M.S.
DRILL & C'SINK FOR 3/8 DIA F.H.S.C.S. - 2 Rs
2 3/4 DIA.
2 1/4 TYP.
6
3
6
1/2
(5) STOP PAD - 4 REQ'D - C.R.S.
DRILL & C'SINK FOR 3/8 DIA F.H.S.C.S.
6
1 1/2
3
1/2
(7) STOP PAD - 2 REQ'D - C.R.S.


A.

Figu

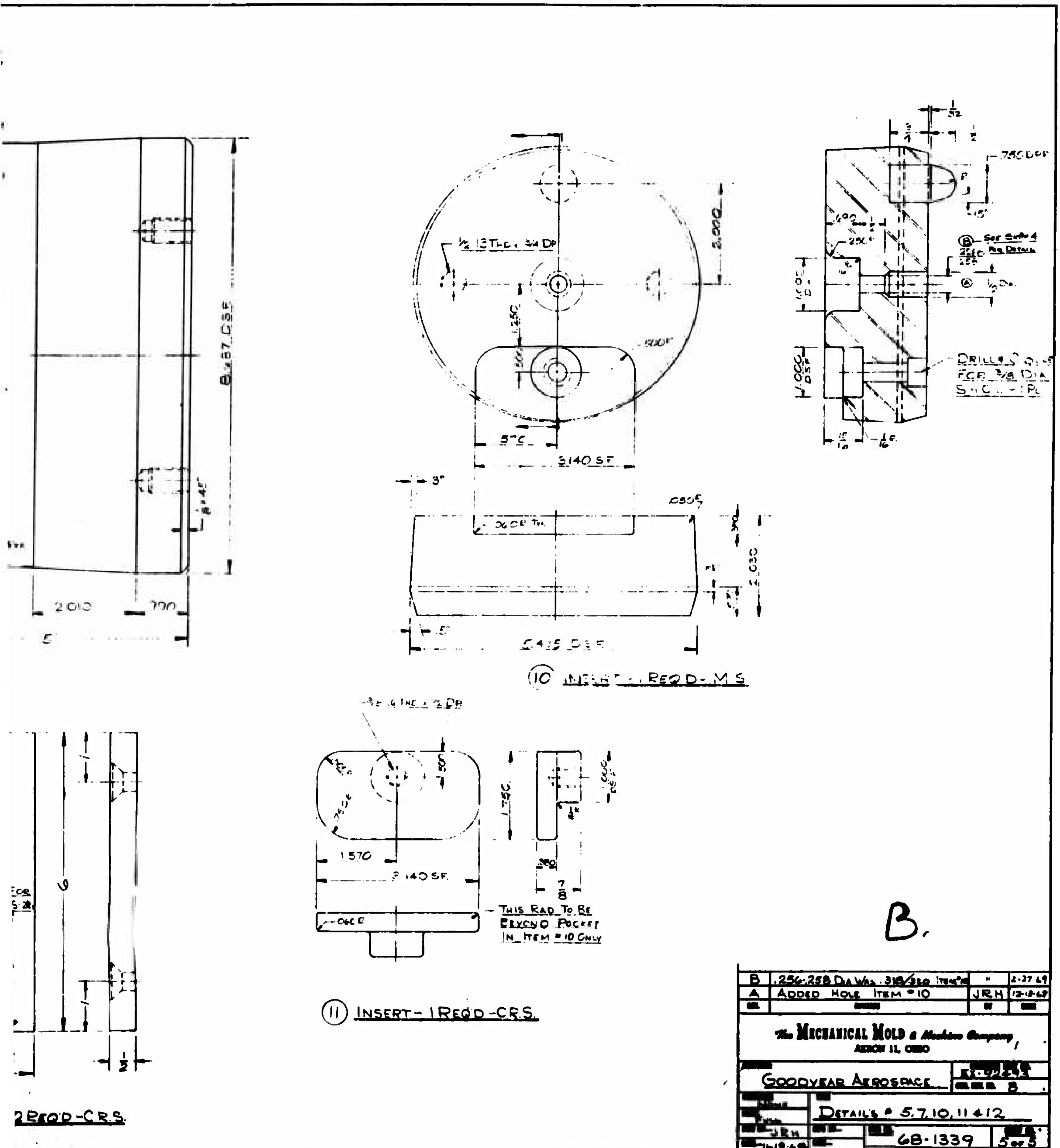
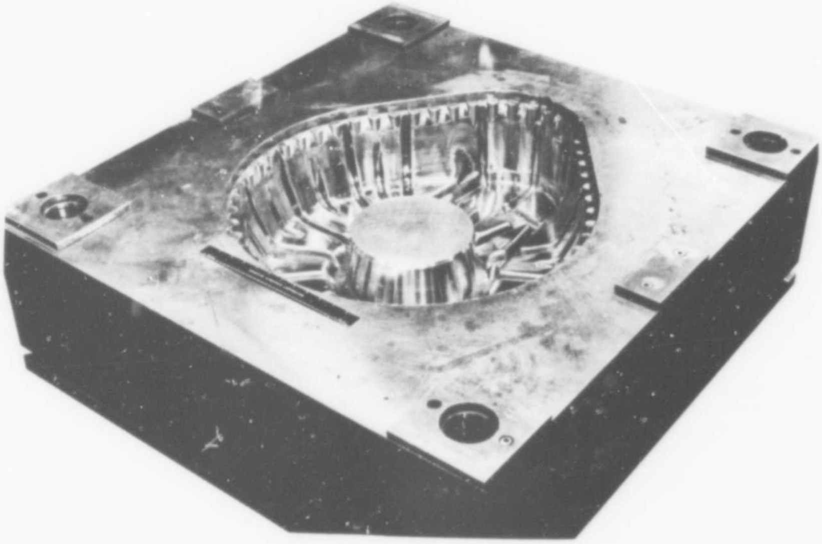
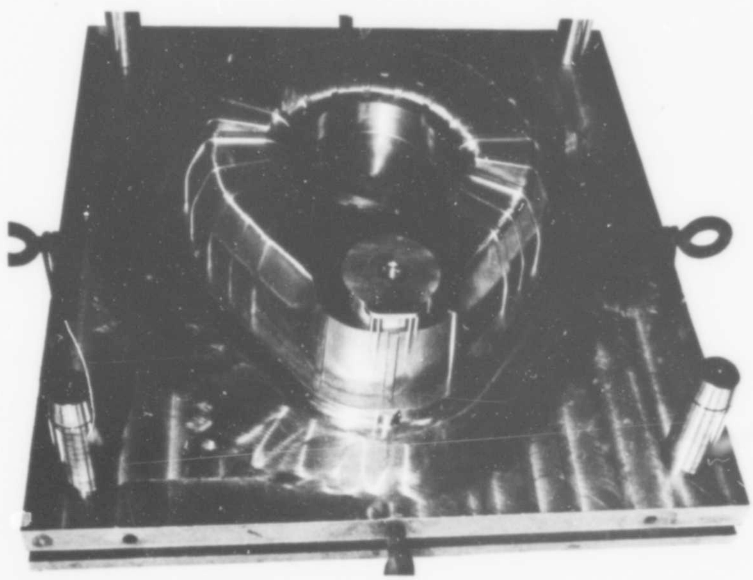



Figure 4-5. Composite front case mold details.



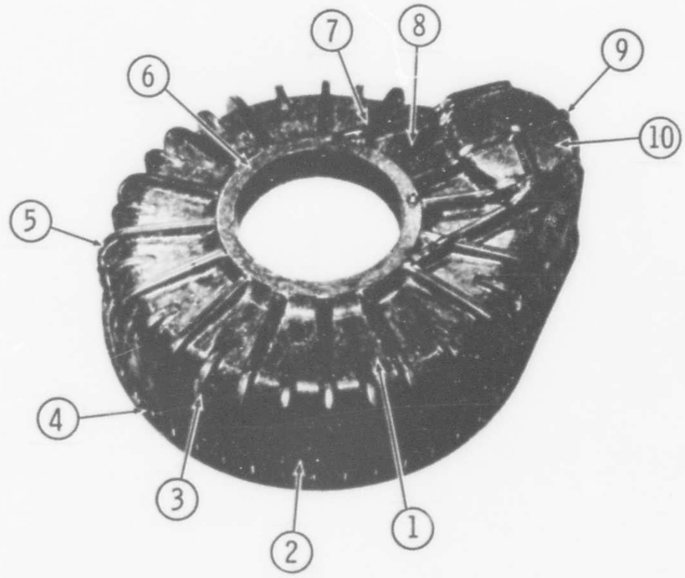
6301-27

Figure 4-6. Composite front case female mold showing recessed areas for placement of external stiffener unidirectional filaments.



6301-28

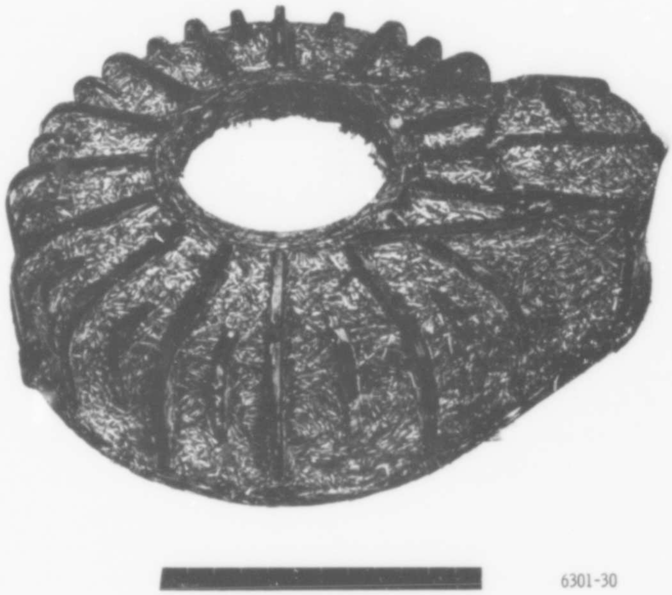
Figure 4-7. Composite front case first male mold with ribs for holding recessed areas on the inner surface.




| | Location | Weight/part (lb) | Total weight (lb) |
|---|---|---|---|
| 1 | Bottom of case | 7.20 | 7.20 |
| 2 | Side of case | 3.48 | 3.48 |
| 3 | Small stiffener, 12 | 0.10 | 1.20 |
| 4 | Connecting ring | 5.96 | 5.96 |
| 5 | Large stiffener, 13 | 0.24 | 3.12 |
| 6 | Center ring | 5.20 | 5.20 |
| 7 | Stiffener, 2 | 0.42 | 0.84 |
| 8 | Stiffener, 2 | 0.18 | 0.36 |
| 9 | Stiffener | 0.39 | 0.39 |
| 10 | Small opening | 1.74 | 1.74 |
| | | | 29.49 |

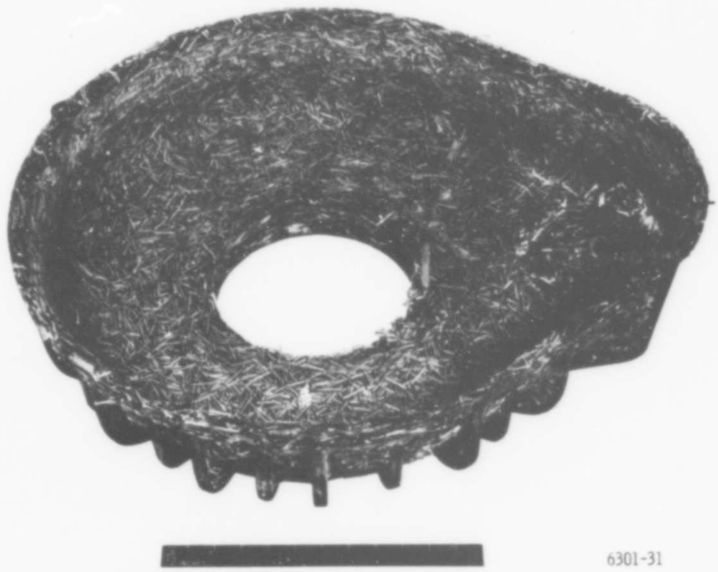
6301-29

Figure 4-8. Composite front case weight sheet.



6301-30

Figure 4-9. Composite front case preform details showing filament orientation and lubrication tube assembly (front view).



6301-31

Figure 4-10. Composite iront case preform details showing filament orientation and lubrication tube assembly (rear view).

Minor abrasions in the recessed areas on the inner wall were blended prior to solvent cleaning and placement of the unidirectional boron stiffener elements. Figure 4-11 shows internal wall characteristics after the first molding operation. To prevent slippage of the unidirectional stiffener filaments a glass cloth bleeder was positioned over the lay-up and the part was placed in a vacuum bag. The air was evacuated and the part placed in an autoclave where the reinforcements were cured for 4 hr at 300°F under 50 psi pressure. Final processing operations removed the bag and bleeder and cleaned the part for shipment. Preliminary review indicates an acceptable molding with zero shrink.

Processing of the second boron case paralleled the first through the primary molding cycle. This unit was of lesser quality as a result of interference with desired random element flow. The flow interference was caused by frayed edges on the boron-impregnated tape elements. The fraying resulted from incomplete encapsulation of the boron with glass. Machinery for making the pressure-compacted fiberglass/boron lamination was modified to prevent reoccurrence of edge fraying. Little experience could be gained by finish molding; therefore, that effort was deleted.

The third boron unit was basically the same as the previous units. Improvements in encapsulation and in obtaining a minimum of loose filaments in the mold charge resulted in an excellent unit. This unit, as the first unit, appears to have experienced no shrinkage.

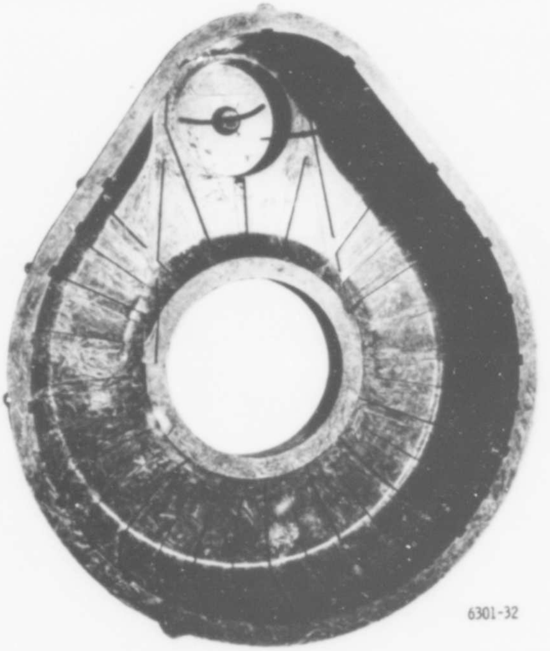



Figure 4-11. Composite front case after first molding operation showing internal wall characteristics.

# V. BIBLIOGRAPHY

Zienkiewiez, O. C. The Finite Element Method in Structural and Continuum Mechanics. Great Britain, McGraw-Hill, 1967, pp. 89-124.

Przemieniecki, J. S. Theory of Matrix Structural Analysis. McGraw-Hill, 1968, pp. 70-83.

UNCLASSIFIED
Security Classification

**DOCUMENT CONTROL DATA - R & D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Allison Division of General Motors<br>Indianapolis, Indiana | 2a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED<br>2b. GROUP |

3. REPORT TITLE
PHASE I LIGHTWEIGHT GEARBOX COMPOSITE CASE
FINAL REPORT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final (July 1968 through June 1969)

5. AUTHOR(S) (First name, middle initial, last name)
Kempinger, G. H.; Wagner, D. A.

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| 30 June 1969 | 51 | None |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>N00019-68-C-0514<br>b. PROJECT NO.<br>c.<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>EDR 6301<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) |

10. DISTRIBUTION STATEMENT
UNLIMITED

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>Naval Air Systems Command<br>Department of the Navy<br>Washington, D.C. |

13. ABSTRACT

This report outlines the work done by Allison Division of General Motors and Goodyear Aerospace Corporation on the design and fabrication of a reduction gear front case made of composite material. The purpose of the program was to demonstrate the feasibility of producing a gear case made of boron-fiberglass composite material. Two gear cases were successfully completed by Goodyear Aerospace Corporation at Akron, Ohio. The cases were fabricated using a pressure-molding process. The design of the composite case is based on the design of the T56-A-18 magnesium reduction gear front case. The new design made use of the high modulus for boron filaments to obtain a composite case that is expected to be twice as stiff as the magnesium case and 13% lighter. Composite materials also have corrosion resistance properties which are superior to those of magnesium and aluminum.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Composite Material Gearbox Case | | | | | | |
| Boron/Fiberglass Composite | | | | | | |
| Unidirectional Fibers | | | | | | |
| Randomly Oriented Fibers | | | | | | |
| Direct Stiffness Method | | | | | | |
| Tool Tryout | | | | | | |
| Composite Case Molding | | | | | | |
| Equivalent Section Method | | | | | | |
| Deflection Analysis | | | | | | |
| Beam and Plate Analysis | | | | | | |